Acoustics of Buildings

By the Same Author

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Acoustics of Buildings

including

Acoustics of Auditoriums and Soundproofing of Rooms

by

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THIRD EDITION

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PREFACE

The third edition of this book has involved a rewriting of the text to take account of the developments in architectural acoustics during the past ten years. New illustrations and examples are cited, with numerous references to investigational work. One important new feature is the introduction of problems to set forth the important elements of the subject, and to serve as an aid in teaching. The text material divides logically into three parts: general phenomena of sound that apply to buildings, acoustics of rooms, and sound insulation.

No account of the acoustics of buildings would be complete, in the opinion of the writer, without a recognition of the pioneer, painstaking work done by Professor Wallace C. Sabine. Until the subject engaged his attention in 1895, but little was known definitely about the action of sound in auditoriums and buildings. His perseverance and insight into the problem led to a formulation of the essential factors of the acoustics of auditoriums and, later, to the inauguration of a general investigation of the insulation of sound, on which he had made some progress at the time of his death in 1919.

One of the stimulating later advances in the subject was the advent of the talking motion pictures which, during the years from 1925 to 1930, involved strenuous efforts to develop apparatus and conditions for their successful production. Another event of importance was the organization of the Acoustical Society of America in 1929. The *Journal* of this society has published regularly the accounts of current investigations in acoustics, while its *Cumulative Index,* which was started in 1939, together with the *References to Contemporary Papers* published in the *Journal,* serve to keep readers well informed about the developments in the subject.

The advances in the past ten years have been rapid and surprising. The theory of reverberation in rooms has been advanced through a study of the so-called " normal modes " of vibration, and new formulas have been evolved that apply particularly to small rooms. Experimental disagreements in the values of absorbing coefficients are being reconciled by measurements of " acoustic impedance." Extensive tables are now available that give absorption coefficients of materials, including those of recent development; also, they give additional information about soundproof constructions. Fletcher's study of loudness has resulted in formulas and graphs that allow explanations of sound energy to be made in terms intelligible to the layman. The author is pleased to note some new confirmations of his theory of ideal auditorium acoustics, which involves special reflecting arrangements for performers and "dead" auditoriums for listeners. The introduction of public-address (sound-amplifying) systems has revolutionized to a considerable extent the acoustical conditions in auditoriums, presenting new problems for the acoustical engineer. Preliminary attempts are being made to specify standards for acoustic conditions in auditoriums and for the performance of public-address systems.

F. R. WATSON

URBANA, ILLINOIS
August, 1941

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PART I — INTRODUCTION

CHAPTER I

GENERAL PHENOMENA OF SOUND THAT APPLY TO BUILDINGS

Origin and Propagation of Sound. The buzz of a bee, the ringing of a bell, and the whistle of a locomotive are all familiar sounds. On examining them, it is found that the source of the sound is a vibrating body. The wings of the bee move rapidly back and forth; the metal of the bell vibrates; and the steam in the whistle pulsates. Figure 1*a* shows the spattering of water set up by a vibrating tuning fork. When the prong of a tuning fork moves forward, it compresses the air in front of it, and the pressure thus formed is relieved when it spreads rapidly outward in the surrounding medium. As the fork prong recedes, it creates a partial vacuum (rarefaction) which also spreads out in the medium, following the compression. These compressions and rarefactions constitute sound waves that push and pull on the ear drum, thus setting up the sensation of hearing. Figure 1*b* gives an idea of the process. As the tuning fork prongs move back and forth, they set up compressions and rarefactions as already explained. Imagine that the small circles in Fig. 1*b* represent little portions of air, while the springs, which are entirely imaginary, show the elasticity ("spring") of the air. Each particle of air moves back and forth as

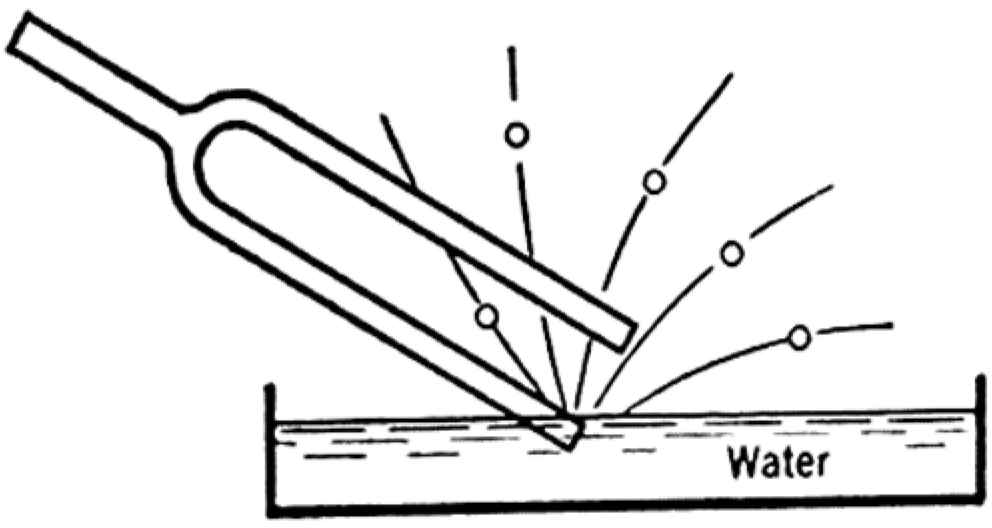

FIG. 1*a*. A tuning fork vibrates when it generates sound.

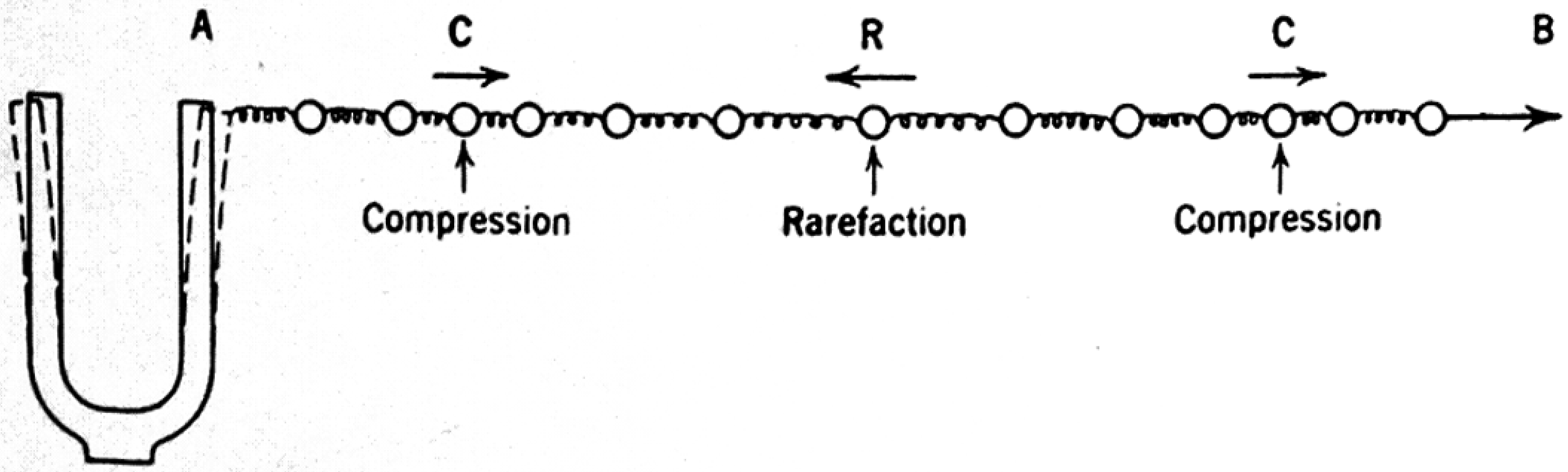

FIG. 1*b*. Diagram showing how a tuning fork compresses and rarefies the air, thus setting up sound waves.

the sound waves pass with a " simple harmonic motion," similar to the motion of the bob of a pendulum, only faster and with extremely small displacements.

Several details of the sound waves should be noted. The air particles are not shot off from the tuning fork, but each one " quivers " back and forth through a minute distance of about one-thousandth of an inch for an average sound. The compressions and rarefactions of the waves are also very small, amounting to approximately one-millionth of the atmospheric pressure. In spite of the smallness of these pressure variations, the ear is able to detect them, thus indicating the sensitivity of hearing and the correspondingly difficult problem in buildings to reduce the sound energy enough so that it will not be disturbing to listeners.

Velocity of Sound. Sound travels very rapidly in air, as fast as a rifle bullet, about 1,120 feet per second at ordinary temperature. Because of this great velocity, sound in a room fills the entire volume in a short time. For example, if two walls are 20 feet apart, the number of reflections of sound per second between them will be: 1,120 ÷ 20, or 56 reflections.

Numerically, the velocity V can be determined by the product of the frequency f and the wavelength L, ($V = f \times L$). For example, if the frequency of the fork in Fig. 1*b* is 224 cycles per second, the wavelength is 5 feet, and the velocity $V = f \times L = 224 \times 5 = 1{,}120$ feet per second. Generally, the velocity in any medium depends on the elasticity and density. The velocities of sound in some common media are shown in Table 1*a*. It is to be noted that the velocity is greater in solids, less in a liquid, and smallest in the air.

TABLE 1*a*

VELOCITIES OF SOUND IN COMMON MEDIA

	Feet per second
Air (15°)	1,120
Water (15°)	4,700
Wood	13,000
Steel	16,500
Brick	12,000

Reflection of Sound. Reflection is one of the very important actions of sound since, as will be shown later, most of the acoustic defects in rooms are due to this phenomenon. In the process of reflection, sound waves from a source, such as S in Fig. 1*c*, which are incident on a wall at angles a, a', are reflected through equal angles, a, a', and appear to come from a point S' which is just as far back of the reflecting surface as the source is in front.

One of the usual examples of reflection in rooms is shown in Fig. 1d. Sound waves starting from a speaker, *S*, progress to a curved wall and are reflected and focused at a point close to the speaker. If the speaker were located at a point *O* on the axis of the curve at the center of curvature, the reflected sound would be focused at the same point.

In case the curved wall is convex, as shown in Fig. 1*e*, the reflected sound is diverged. Such surfaces are being used in rooms as a means of approximating the desirable " diffuse " sound.

Echo. In case the reflected sound arrives about $\frac{1}{15}$ of a second later than the sound directly from the speaker, an auditor will get a disturbing echo. If the time lag becomes less than about 0.05 second, the merging is beneficial, as explained later under *interference.*

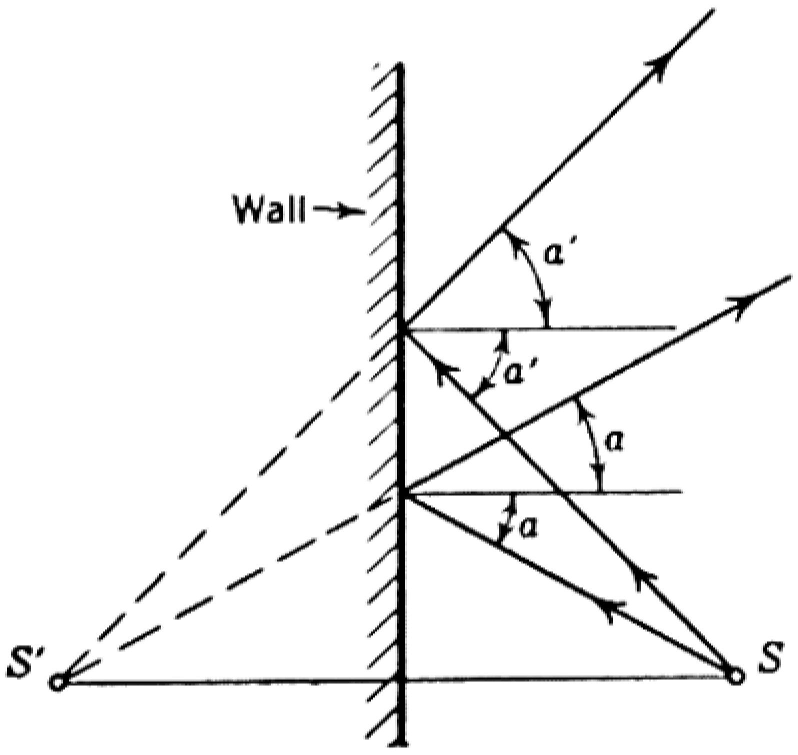

FIG. 1*c*. Equal angles of incidence and reflection of sound.

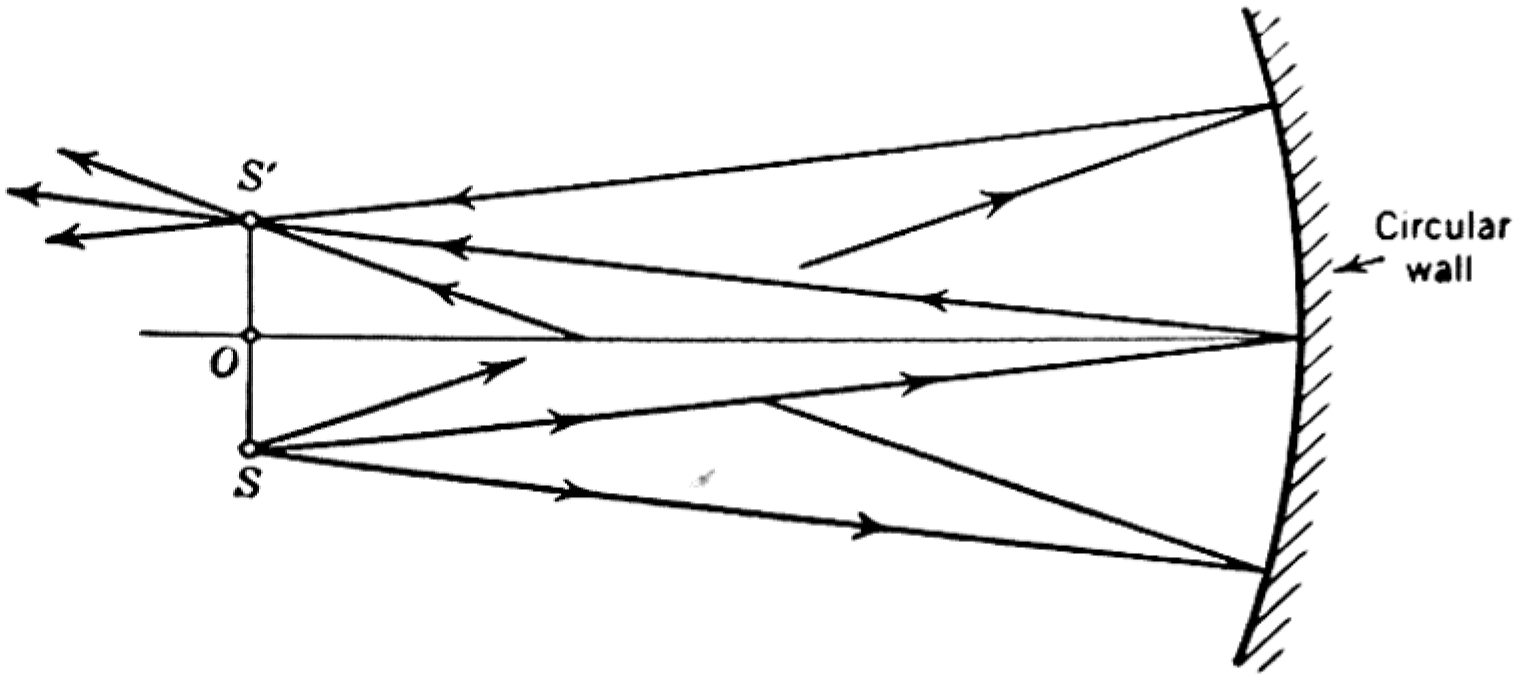

FIG. 1*d*. Reflection and focusing of sound by a curved wall.

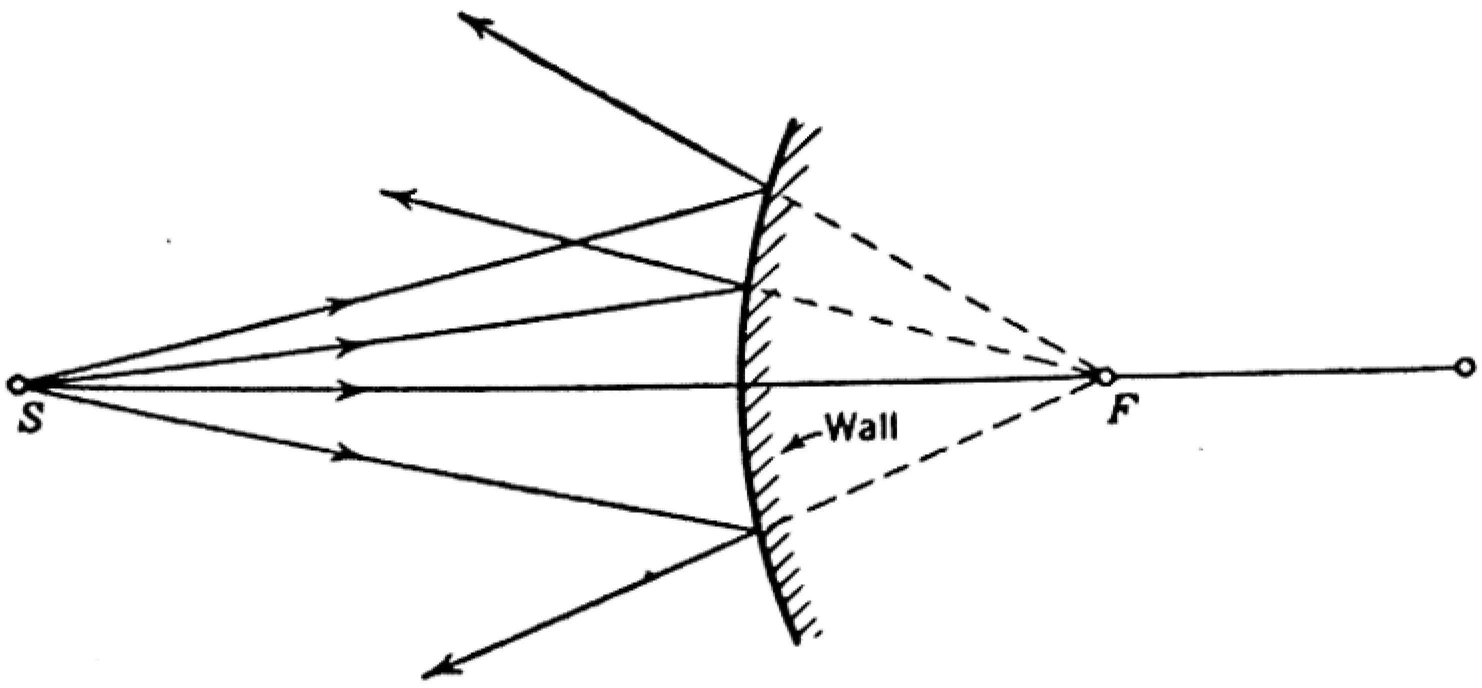

FIG. 1*e*. A convex wall diverges the reflected sound.

Parallel Walls. Repeated reflections between parallel walls set up a " flutter " of sound which is undesirable. For example, the high, hard-plaster side walls of some churches allow back-and-forth reflections of sound that become objectionable in seats a few rows back from the speaker. In smaller rooms, the flutter effect sets up disturbing resonances. This defect can be reduced somewhat by making the walls non-parallel and by lining them irregularly with special arrangements of absorbing materials, a difficulty that has not been completely solved at the present writing.

Reflection of Sound in Auditoriums. The preceding discussion shows some of the disturbances set up in rooms by reflected sound, and indicates the necessity of making a serious study of the *shape* of an auditorium to avoid some of these troubles. Focusing walls are especially objectionable. Their action may be reduced by substituting plane or convex walls, and by installing grill work or strips of absorbing material, as explained under " diffraction."

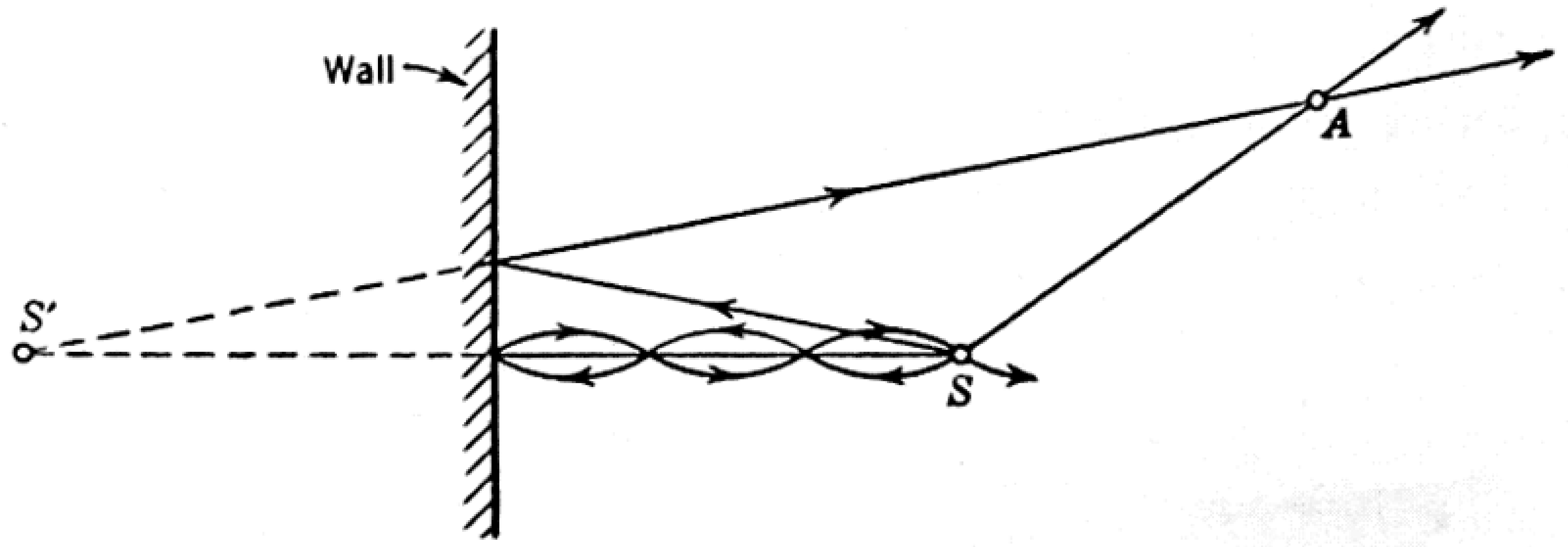

FIG. 1*f*. Sound reflected from a wall interferes with the direct sound and produces standing waves.

Interference of Sound, Standing Waves, Blurring, Resonance. If a speaker S stands near a wall, Fig. 1*f*, an auditor A will get the sound that comes to him directly from the speaker and also the sound that is reflected from the wall. These two sounds will combine and produce an *interference*. If the compressions (and rarefactions) of the direct sound combine with the compressions (and rarefactions) of the reflected sound, the resultant effect will be louder than for either sound alone. If, however, the compressions of the direct sound combine with the rarefactions of the reflected sound, the resultant will be weaker. If a whole number of half waves are set up between parallel walls, a reinforcement of sound, or a *resonance,* is set up. In between the speaker and the reflecting wall, *standing waves* will be set up as the result of the combination of the direct and reflected sounds. In large rooms, these interferences and standing waves are usually unimportant, but in small rooms, such as broadcasting and receiving chambers, they set up resonances that are serious drawbacks, as discussed in the following chapter. Many people discover these resonances when they sing in a bathroom. If the reflected sound, as in Fig. 1*f*, reaches the auditor more than about 0.05 second later than the direct sound an interfering " blurring " of speech is probable, thus explaining the " dead spots " in auditoriums. (See Chapter X under " Blurring of Speech.")

Beats of Sound. If two sources of sound of slightly different frequencies are operated at the same time, a pulsating effect of loudness, called " beats," is created. Suppose that at a certain instant two tuning forks *A* and *B*, mounted on resonance boxes, Fig. 1*g*, are both sending out compressions. Observers will hear a combined sound, louder than the sound from either fork alone. A short time later, since the forks differ in frequency, one fork will be giving out a rarefaction while the other is giving out a compression, resulting in a decrease in the sound heard. After a similar interval of time, the compressions will again unite, and so on. The observer near by thus gets regular fluctuations in the loudness that are called " beats." If the two sources have equal intensities and are near each other, the resulting fluctuations are quite marked. The frequency of the beats depends on the difference in frequencies of the two sources. For example, if the frequencies are 100 and 102 cycles per second, respectively, there will be 2 beats per second.

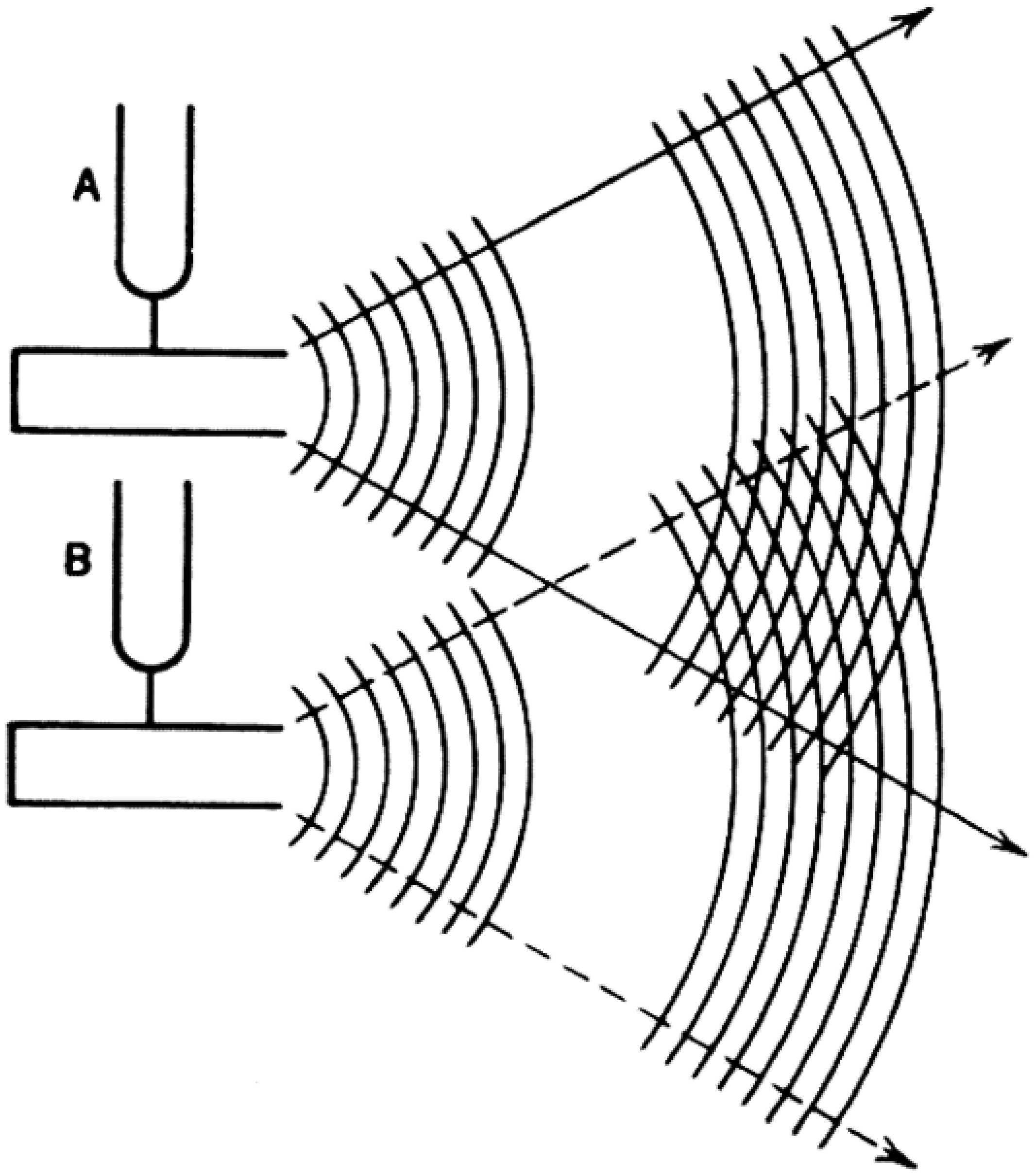

FIG. 1*g*. " Beats " of fluctuating loudness are set up by the overlapping sounds from two tuning forks that have nearly the same frequency.

Diffraction of Sound. When sunlight shines through a small hole in a wall, a well-defined beam is seen by reflection of light from the motes in the air. Sound, however, in passing through this hole, will spread out in spherical waves, with the hole at the center. This spreading effect is known as *diffraction* and is one of the important actions of sound in buildings.

When incident on a rough plaster wall, light will be scattered and diffracted, while sound, contrary to popular opinion, will be reflected quite regularly, much as if the rough wall were a smooth mirror. This marked difference in the diffraction of light and sound is due to the fact that the average wavelength of audible sound is about one million times greater than the average wavelength of visible light, and correspondingly larger reflecting surfaces and apertures are required for sound if the diffraction effects are to be minimized. In many instances this diffraction of sound is desired in building acoustics.

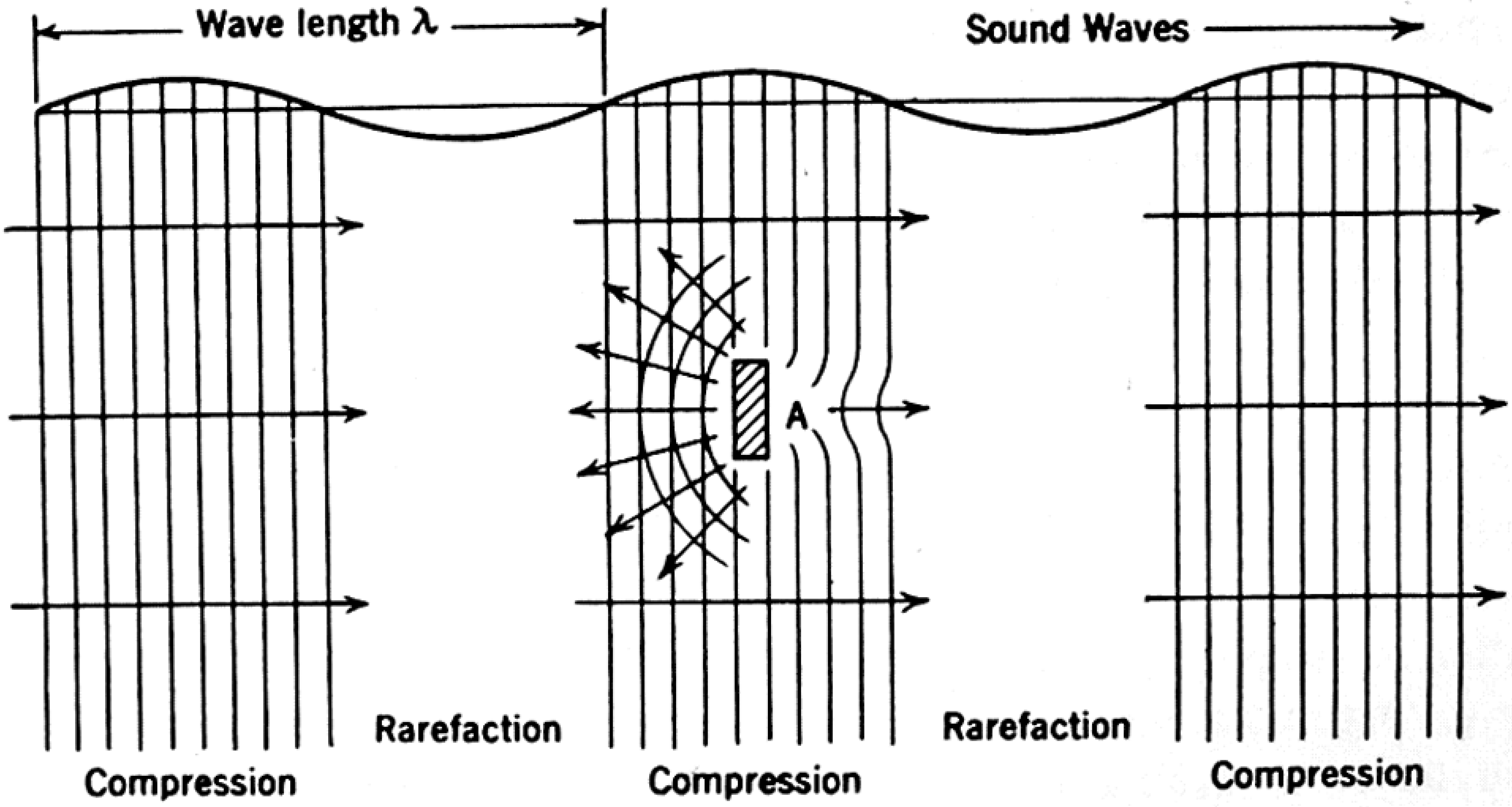

FIG. 1*h*. A small obstacle diffracts sound by reflection.

Sound incident on a small object is diffracted on reflection, as shown in Fig. 1*h*. This diffracting action is instructive when devising means for breaking up the regularity of reflection from walls in an auditorium. For example, if an objectionable reflecting wall is lined with strips of absorbing material of proper widths, alternated with corresponding widths of smooth wall, it is possible to minimize the regular reflection, as in Fig. 1*i*. Diffraction will take place on reflection from both the absorbing strips and the smooth wall sections, but the sections with the material will absorb and reduce the intensity of the sound striking that portion and will also change the " phase " somewhat (i.e., shift the

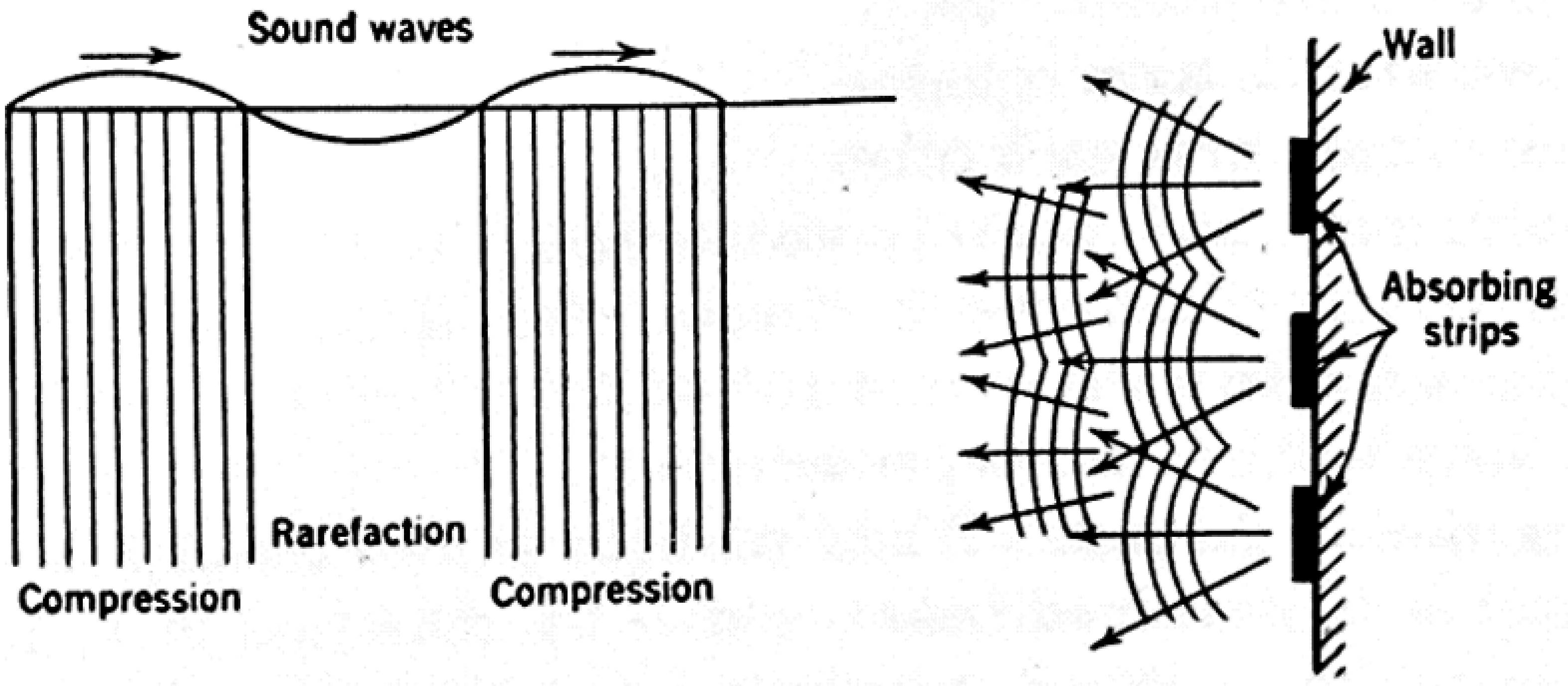

FIG. 1*i*. Diagram showing how narrow strips of absorbing material on a wall diffract sound and disturb regular reflection of sound.

compressions and rarefactions) so that the two sets of reflected waves will interfere and thus give less disturbance than sound reflected from a continuous smooth wall.

There are other illustrations of diffraction in buildings. Thus, sound will be diffracted when passing out through ventilation openings, cracks around or under doors, through the air space below a window partly opened, etc. Sound from electric loud-speakers experiences diffraction. Thus, a loud-speaker with a diameter larger than the wavelength of sound tends to send a beam of sound straight forward, whereas, if the wavelength is large compared with the diameter of the speaker, the sound spreads out in approximately spherical waves, with the loud-speaker at the center. Because of this diffraction effect, two types of speaker are sometimes used in auditoriums, one of large diameter for the low frequencies, and one of small diameter for the high frequencies, so that most of the sound can be directed efficiently to the audience. This directive effect of loud-speakers and the possibility of amplifying sound to make it louder are important new developments in obtaining improved acoustics in theaters and auditoriums.

Musical Sounds. Sound in buildings may be classified as speech, music, and noise, although these are not independent, since they all have the three musical characteristics of frequency, intensity, and tone-structure.

Frequency is defined as the number of cycles per second. Figure 1*j* gives the range of frequencies of the piano and the corresponding values for musical instruments and speech. It is to be noted that the range extends from about 70 to 8,000 cycles for the piano, but covers a smaller range for speech and instruments. These ranges refer to " fundamental " tones; but if the overtones are included the ranges are greater, extending from about 40 cycles for a bass viol to 15,000 cycles for the snare drum and oboe.[1]

Intensity of sound is defined as the flow of sound energy per second through unit area. For average sounds, this energy is very small, about one-millionth of the energy needed to operate an electric-light bulb. In ordinary units, the range of intensities that can be perceived by the ear is enormous, extending from 1 " threshold " unit for a faint sound to 1,000,000,000,000 units for a very loud sound. Smaller *numbers* to express this vast range have been developed by using the *decibel* unit, which is obtained by taking 10 times the logarithm of the intensities. Figure 1*k* represents the range of common sounds in terms of decibels.

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[1] " Frequency Ranges for Musical Instruments," W. B. Snow, *Jour. Acous. Soc. Amer.*, July, 1931.

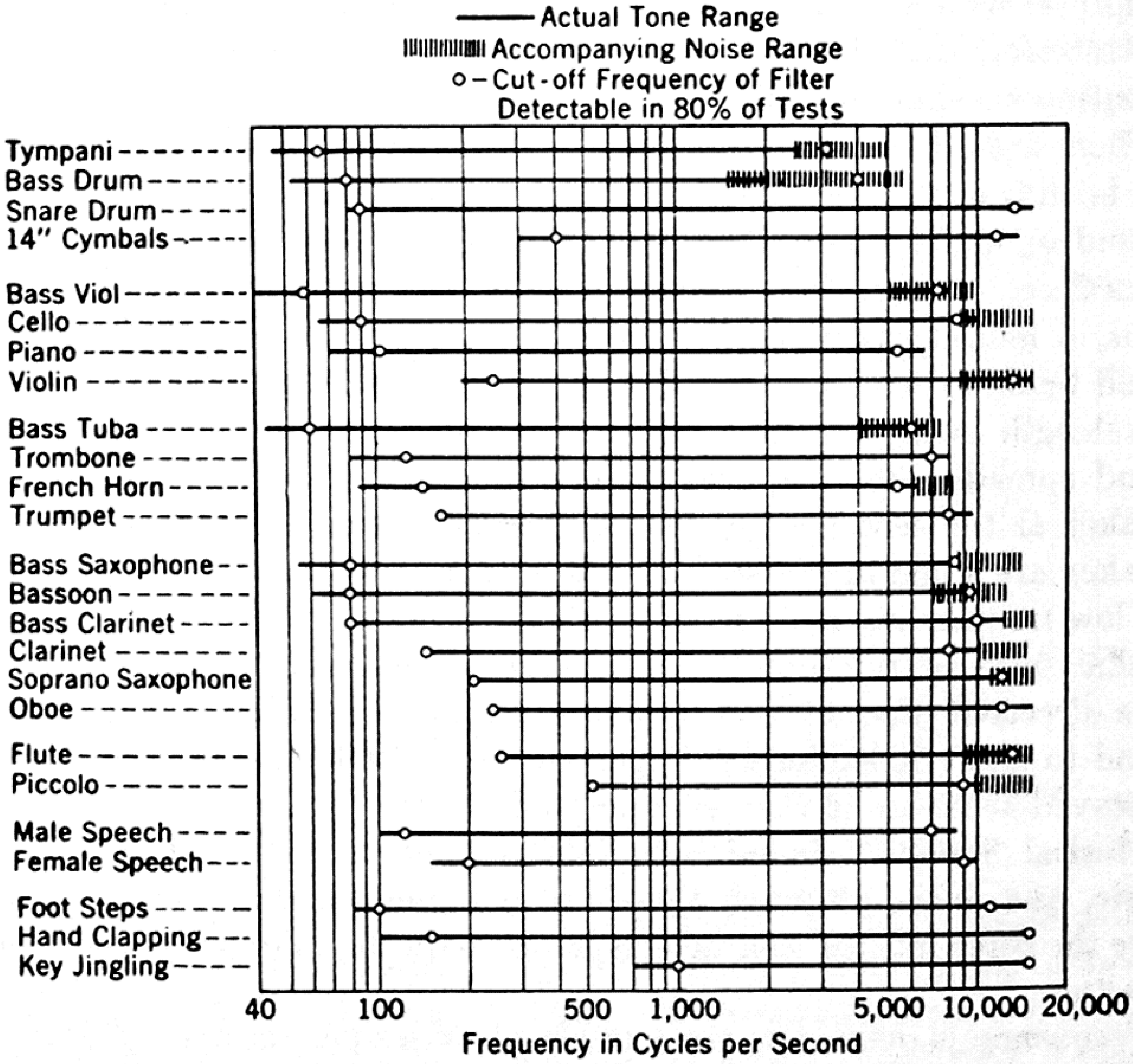

FIG. 1*j*. Frequency ranges for musical instruments and speech.

Intensity—amount of energy in the sound	Decibels	Type of Noise
1,000,000,000,000	120	
100,000,000,000	110	Airplane Engine
10,000,000,000	100	
1,000,000,000	90	Heavy Traffic, Pneumatic Drill
100,000,000	80	
10,000,000	70	Noisy Office, Telephone Conversation, Ordinary Traffic
1,000,000	60	
100,000	50	Average Office
10,000	40	Ordinary Conversation
1,000	30	Quiet Home, Quiet Conversation
100	20	
10	10	Rustle of Leaves, Whisper
1	0	

FIG. 1*k*. Values of common sounds in intensity units and the corresponding decibel numbers.

The third characteristic of sounds is the *tone structure*. It is by this characteristic that various sounds can be distinguished from one another, a piano tone and a cornet for example, even though they both give out the same frequency and intensity. Each one has a more or less complex structure due to the simple tones that enter into the resultant, as shown by the illustrations in Fig. 1*l*.

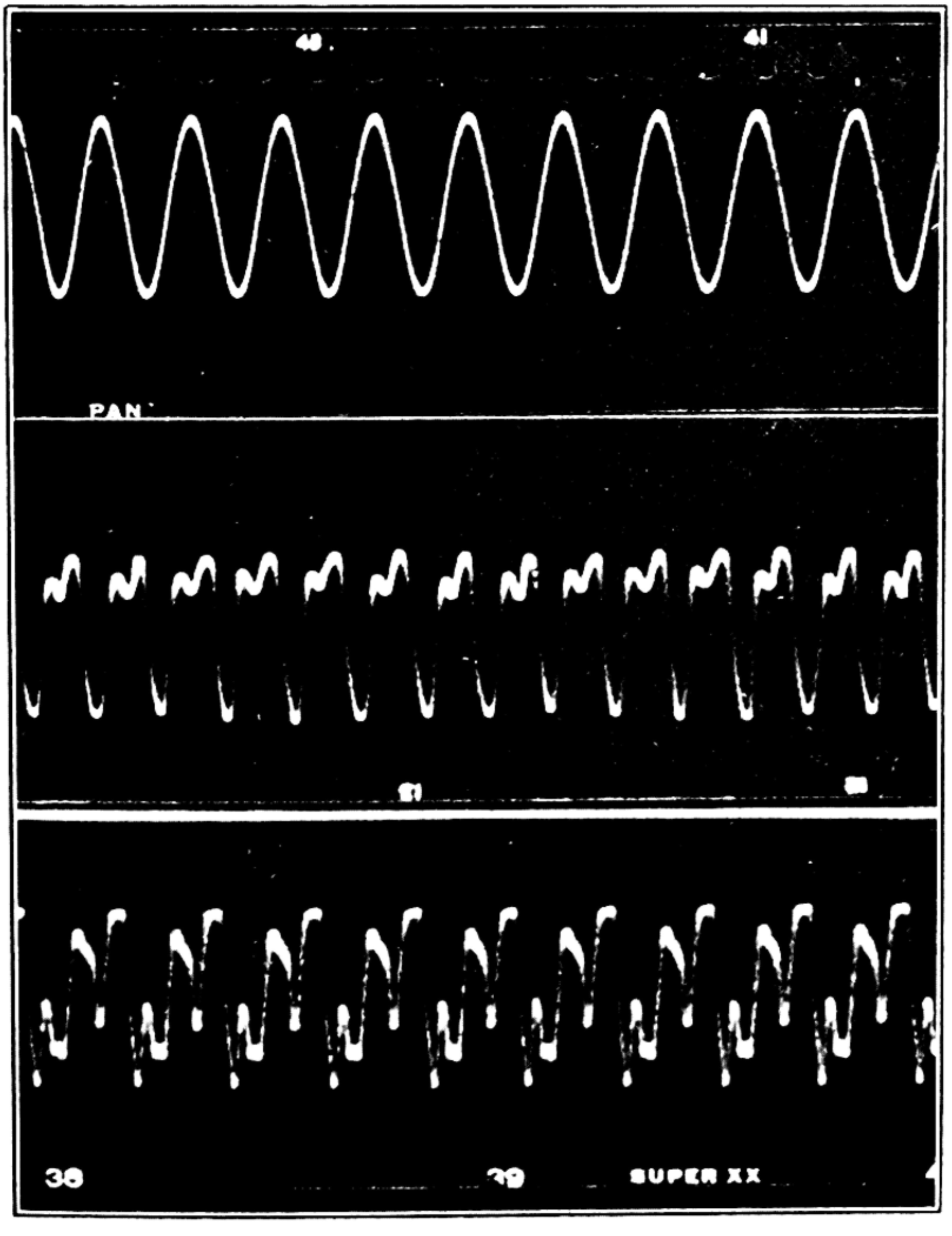

FIG. 1*l*. Resultant tone structure due to several tones.

Top. A pure tone of a single frequency.
Center. A complex sound containing a fundamental tone and the first overtone.
Bottom. A complex sound containing the fundamental, first, second, third, fourth, fifth, sixth, seventh, and tenth overtones.
(From Underwriters' Laboratories, Inc., *Bulletin of Research*, No. 17.)

Sounds can be visualized or recorded by various devices. One of the most useful instruments is the *oscilloscope*, pictured in Fig. 1*m*. The sound to be studied impinges on a microphone and is converted into an electric current, which is amplified and led into the oscilloscope and causes a stream of electrons to oscillate and trace out on a fluorescent screen a wavy form that is characteristic of the sound. These waves can be photographed or can be studied visually. The complex wave form can be separated into the simple waves that make it up, as indicated by Fig. 1*l*.

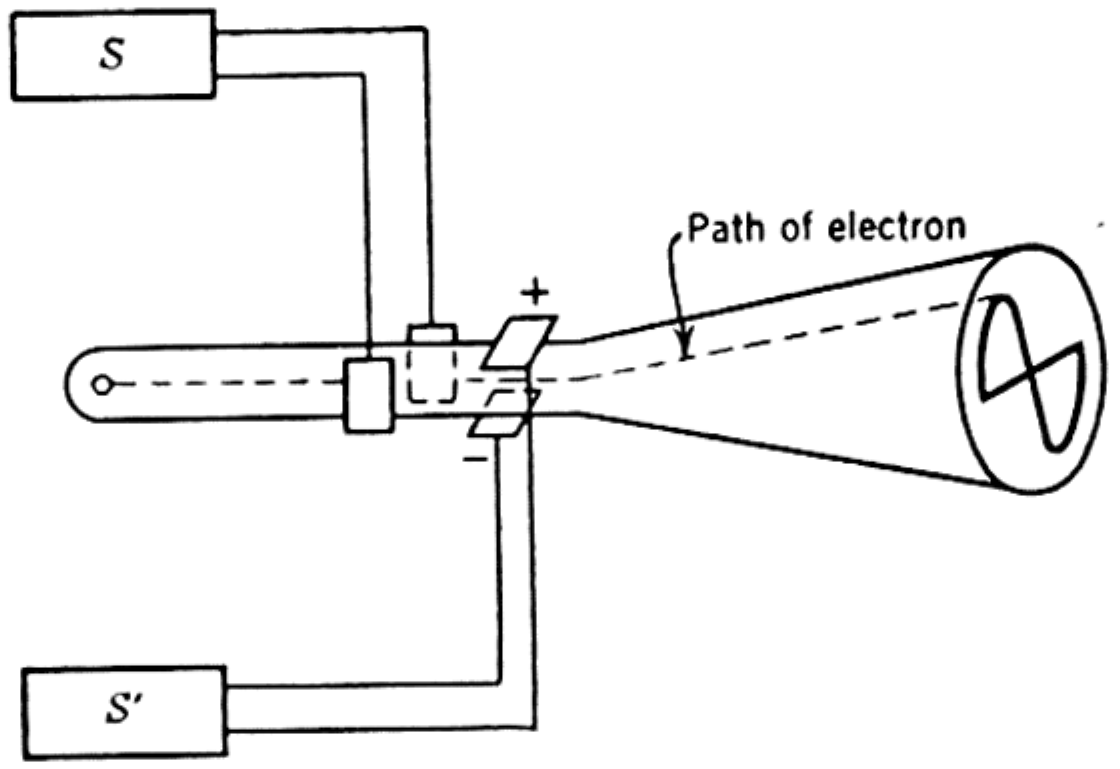

FIG. 1*m*. Diagram of oscilloscope for visualizing sound.

Another instrument that is commonly used for measuring sounds is the *sound-level meter*, Fig. 1*n*, a device that "picks up" the sound with a microphone, converts it into an electric current, amplifies it, and gives the energy values by readings of a galvanometer. These meters not only will show the actual energy of the sounds, but also, by means of separate electrical networks, will give

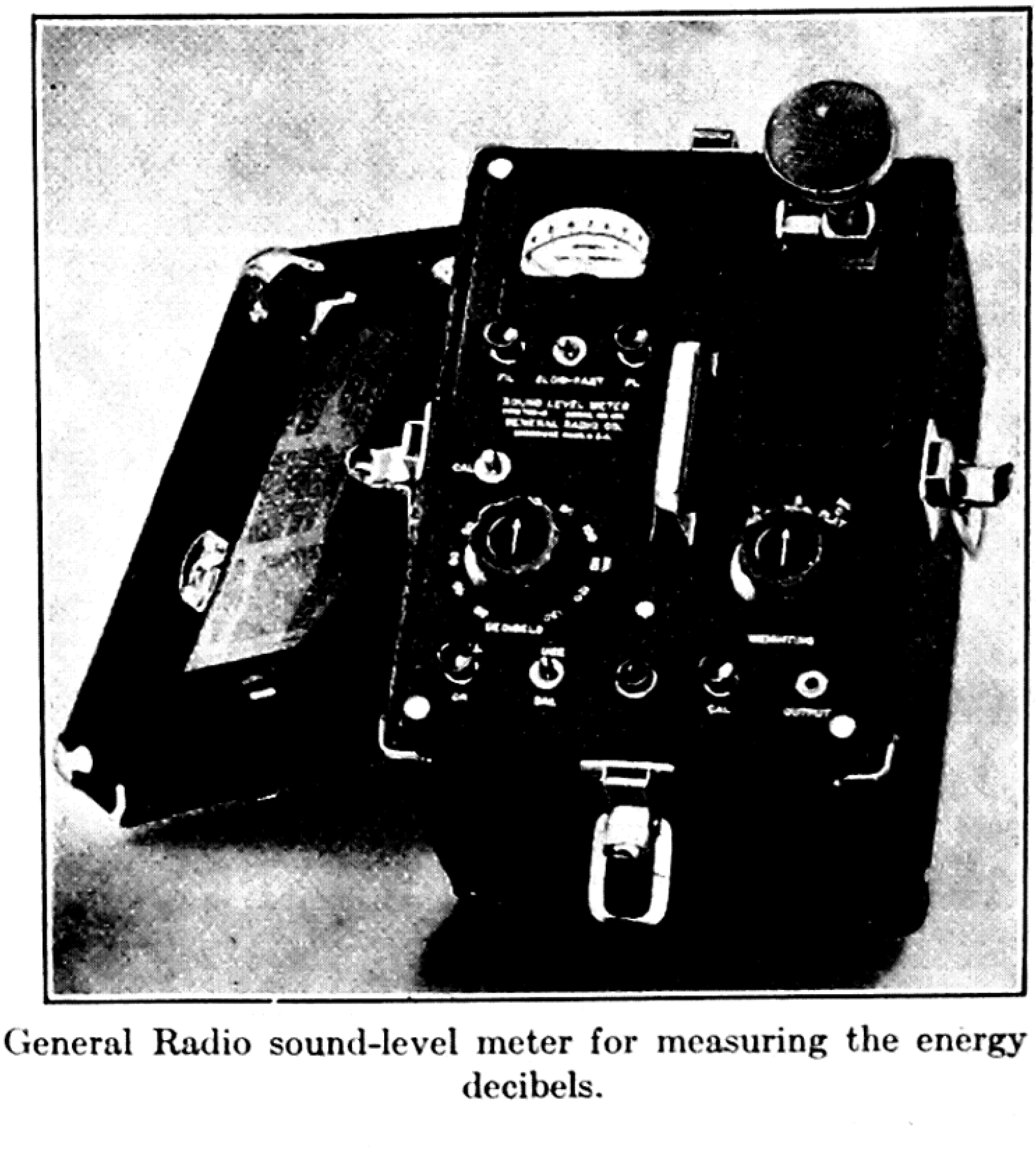

FIG. 1*n*. General Radio sound-level meter for measuring the energy of sound in decibels.

readings comparable with what the ear hears. For example, a sound of 60 decibels actual intensity may appear to the ear as only 35 decibels.

In the control and reduction of sound and noise in buildings, it is first desirable to find the characteristics of the sound under consideration, since sounds vary widely. On the basis of this information, it is then possible to apply corrective measures suitable to the sound in question, selecting and installing materials with absorbing properties that will affect the sound; by changing the shape of the walls to act efficiently on the sound analyzed, etc. This scientific procedure is coming into more common use with acoustical engineers.

Hearing. Any adjustment of sound in buildings is made for the convenience and comfort of the occupants, and therefore, if done intelligently, it should take into account the performance of the ear and the phenomena of hearing. Extensive experiments in this connection have been made by the Bell Telephone Laboratories because of the importance of speech and hearing in telephony. Figure 1o gives some of the results obtained, showing the sounds that can be perceived by the human ear. The lower curve indicates the "threshold of hearing," that is, the faintest sounds at various frequencies that can be heard by persons with normal hearing; the upper curve indicates the loudest sounds that the ear can endure. The area between these curves gives all the sounds, with regard to frequency and intensity, that can be perceived. It is to be noted that the range of frequencies is approximately from 30 to 16,000 cycles per second, and the intensities vary about 120 decibels in the region of 1,000 cycles, which means that the painful sound is 1,000,000,000,000 times as intense as the faint threshold sound. The shaded parts of the diagram indicate the sounds of speech and music in ordinary use, very low-frequency sounds being seldom in

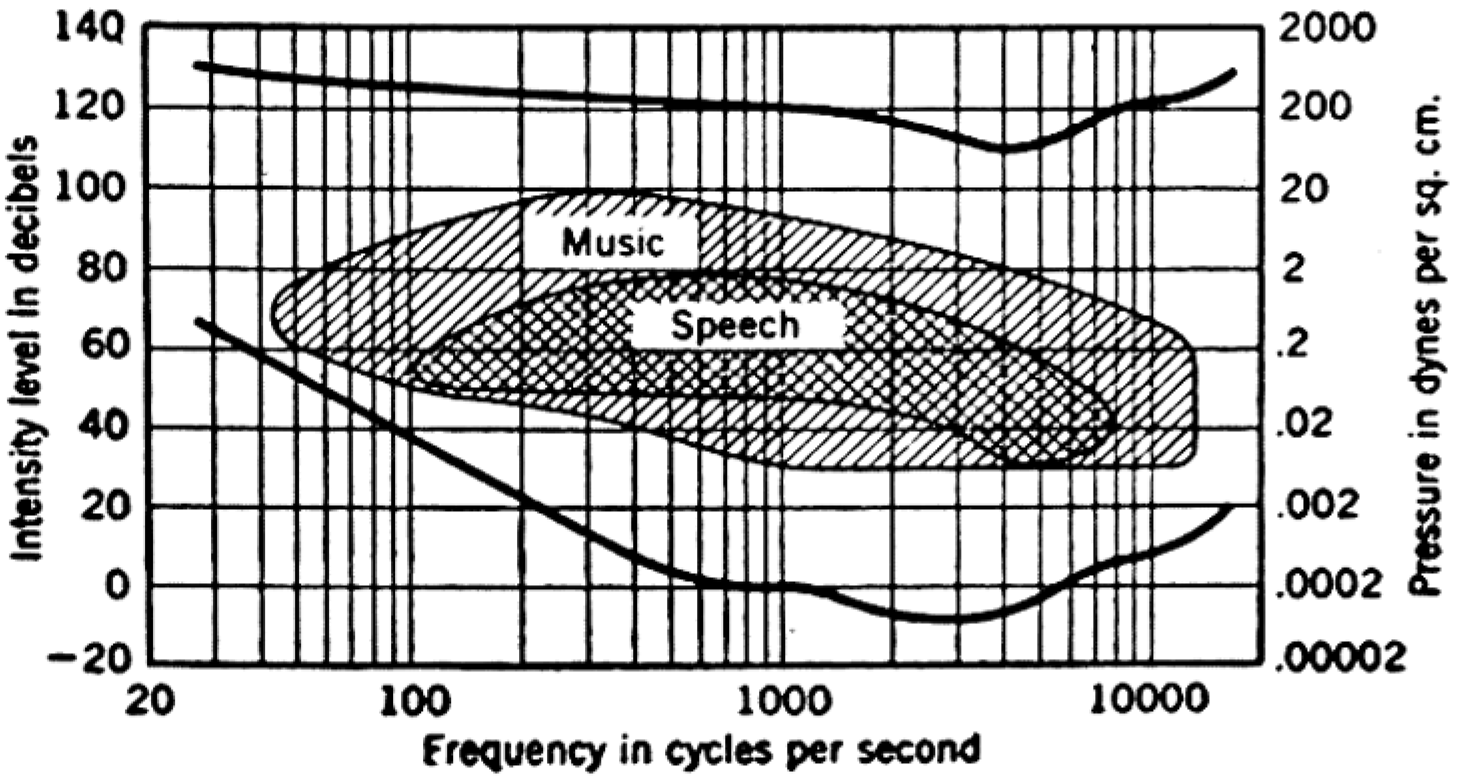

FIG. 1o. Diagram showing the sounds that can be heard by the human ear. (From *Bell Laboratories Record*, June, 1934.)

evidence. Hard-of-hearing people perceive only part of the sounds, roughly shown by the shaded areas, the exact amount depending on the extent of the deafness.

Loudness. In controlling noise in buildings, it is usually necessary to know the characteristics of the noise, particularly how loud it is. The determination of loudness has not been an easy matter. A number of investigators have performed experiments apparently without agreement among the different results; but Fletcher, after a study of all the data, including his own, was able to show an agreement and to evolve relations between the intensities of sounds and the corresponding loudness as perceived by the ear. The first step in Fletcher's solution is shown by the " equal loudness curves " of Fig. 1*p*. To determine the loudness of a sound *X*, it is first compared with a standard reference tone of 1,000 cycles per second, the standard values at 1,000 cycles being drawn in curves of 10-db steps above the reference intensity of 0 db, which has the value of 10^{-16} watt per square centimeter, the units for these reference tones being called " phons." For example, it is seen that a sound of 100 cycles per second that has an intensity of 63 db above the 0-db level appears to be equally loud as a 1,000-cycle reference tone that is 40 db (40 phons) above 0 db. If this 100-cycle tone is raised from 63 db to 72 db, or 9 db, the increase in the corresponding 1,000-cycle tone is from 40 db to 60 db, or an increase of

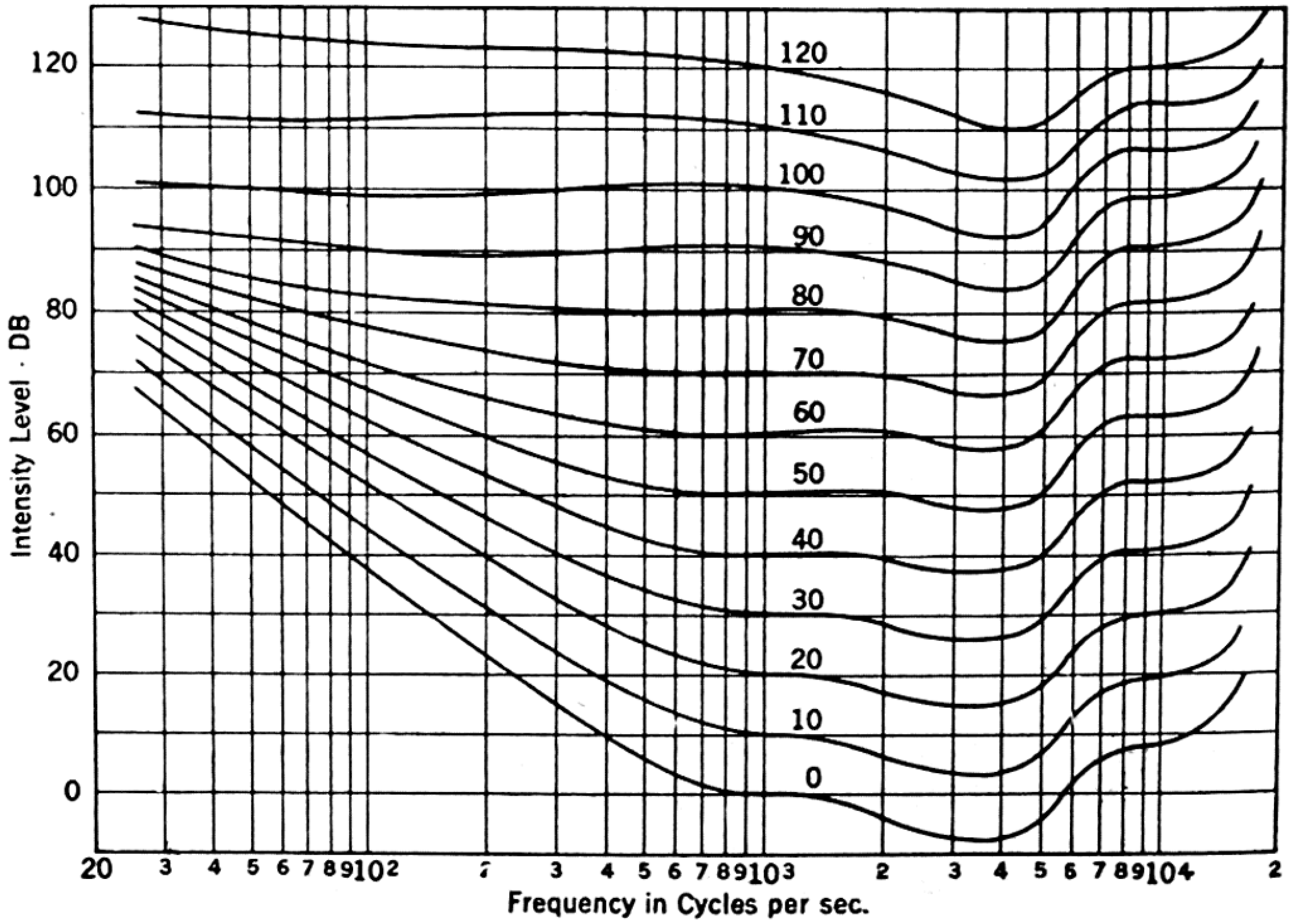

FIG. 1*p*. Equal loudness level curves. (Fletcher and Munson, *Acous. Jour. Amer.*, October, 1934.)

20 db. In the same manner, any complex sound may be compared for equal loudness with a 1,000-cycle reference tone.

The second step in Fletcher's solution is to interpret the value of L phons of the 1,000-cycle tone in terms of the loudness number N as perceived by the ear. For this purpose, the graph in Fig. 1q has been drawn by Fletcher after his study of the results obtained by the various investigators. For example, suppose that the value of the 1,000-cycle tone when adjusted to appear equally loud as an unknown sound X is $L = 40$ db. Reference to the graph in Fig. 1q shows that the corresponding loudness number $N = 1{,}000$ units. Now suppose that the unknown sound X is increased in intensity until the equal 1,000-cycle tone has the value $L = 70$ db, for which the loudness number from Fig. 1q is $N = 10{,}000$ units. The loudness has thus been increased from 1,000 to 10,000, meaning that it has been made ten times louder; but it is interesting to note that the *intensity* of the sound has been increased *1,000 times* (from 40 db to 70 db). Further use of this important relation is explained in the problems that follow, and in the chapter on field tests.

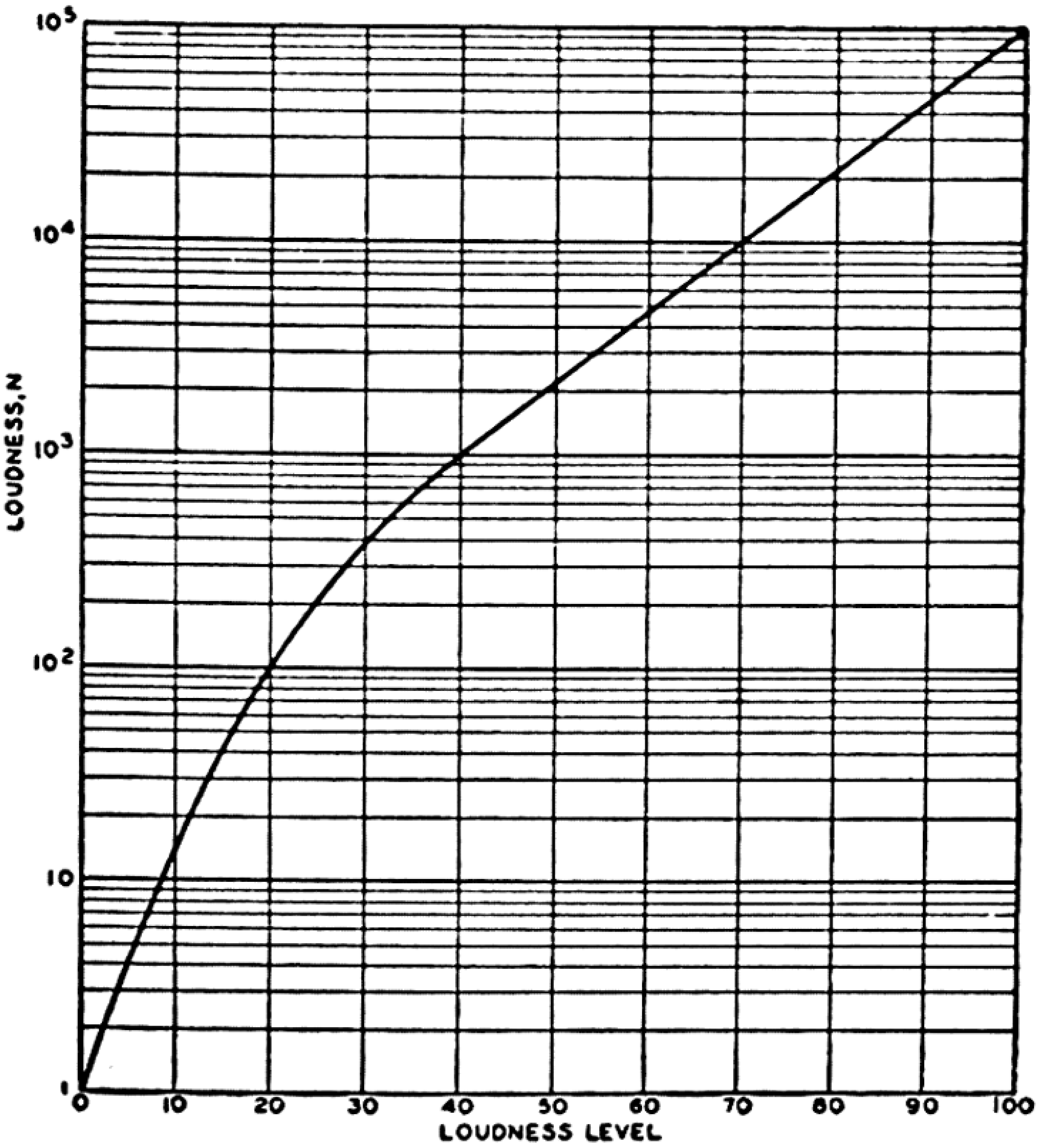

FIG. 1q. Graph giving the relation between a standard reference 1,000-cycle tone in "phons" and the corresponding loudness number perceived by the ear. (Fletcher and Munson, *Acous. Jour. Amer.*, Vol. 9, pp. 1–10, 1937.)

PART II — ACOUSTICS OF ROOMS

CHAPTER II

BEHAVIOR OF SOUND IN A ROOM

How Sound Fills a Room. When a speaker addresses an audience, the sounds he utters proceed outward in spherical waves until they strike the boundaries of the room, where they are reflected, transmitted and absorbed in varying amounts, depending on the character of the walls. Figure 2*a* pictures a pulse of sound in a room 60 feet long and 40 feet wide, $\frac{1}{60}$ second after it has started from the speaker at *S*. The pulse travels rapidly, about 1,120 feet per second at ordinary temperatures, so that, by successive reflections, it rapidly fills the room. In the meantime, the energy of the pulse is diminished at each reflection by the absorption of a fraction of the incident sound, with the result that it gradually dies out.

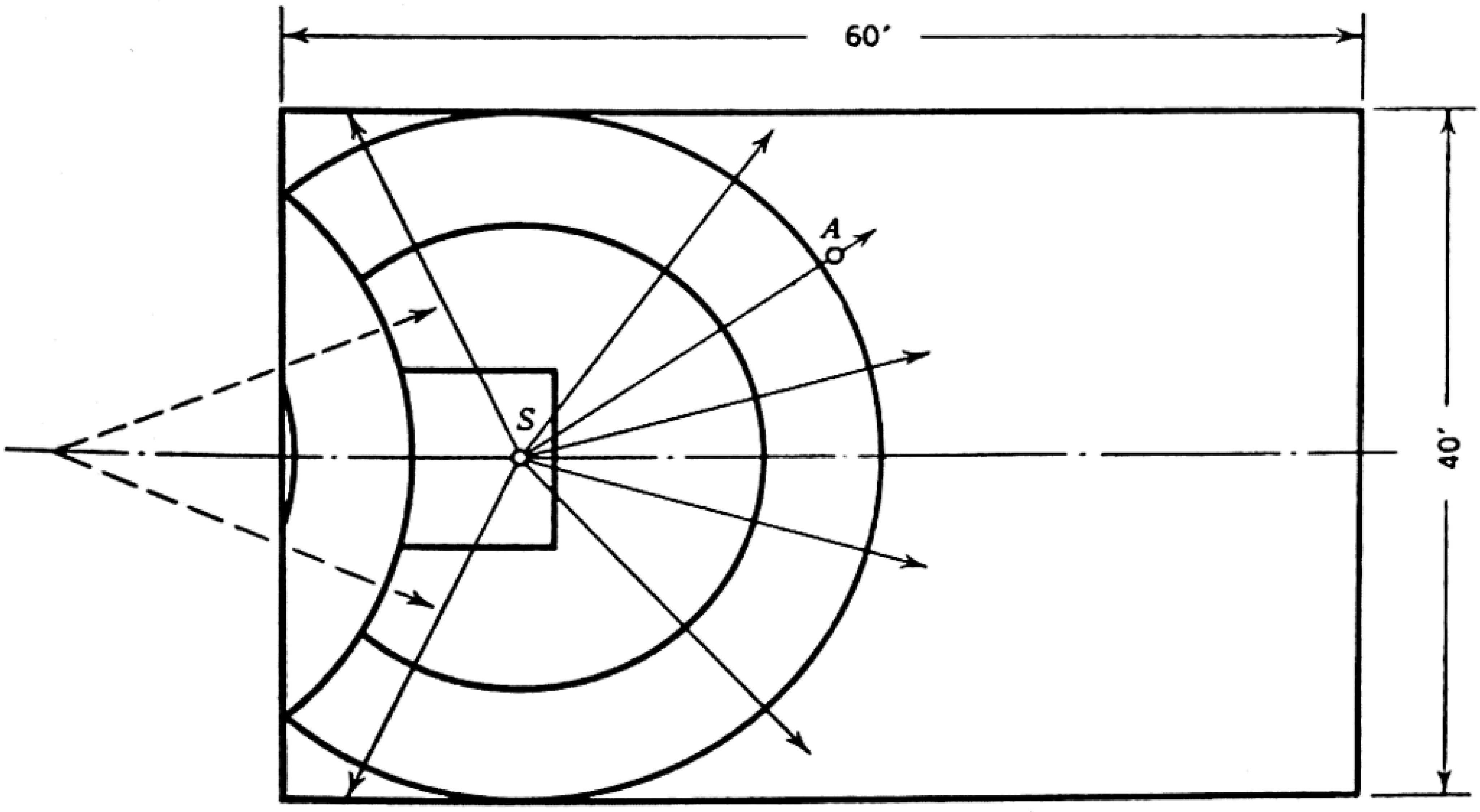

FIG. 2*a*. Pulse of sound in a room $\frac{1}{60}$ second after leaving the source, *S*.

Figure 2*b* shows the pulse of sound $\frac{1}{60}$ second later than in Fig. 2*a*, and indicates the increasing reflections and interference of the waves. The imagination readily supplies the details after $\frac{1}{10}$ second has elapsed, when sound has been reflected many times, not only from the walls, as pictured, but also from the ceiling and the floor, so that every element of volume in the room is filled with waves proceeding in every direction.

The pulse pictured in Figs. 2*a* and 2*b* is a special case of a sound of much shorter duration than those usually met with in auditoriums. A simple musical tone, for example, consists of a series of compressions and rarefactions that follow each other in regular succession. Speech sounds are musical in nature, but are usually more irregular and shorter in duration than musical sounds. Figure 2*c* is a photograph of water waves that are analogous to waves of a simple musical sound in an auditorium.[1] A thin metal strip, shaped so as to give a miniature outline of the auditorium, was laid flat on the glass bottom of a tank of shallow water. By directing puffs of air on the water surface, waves were generated that proceeded outward in circles and were reflected

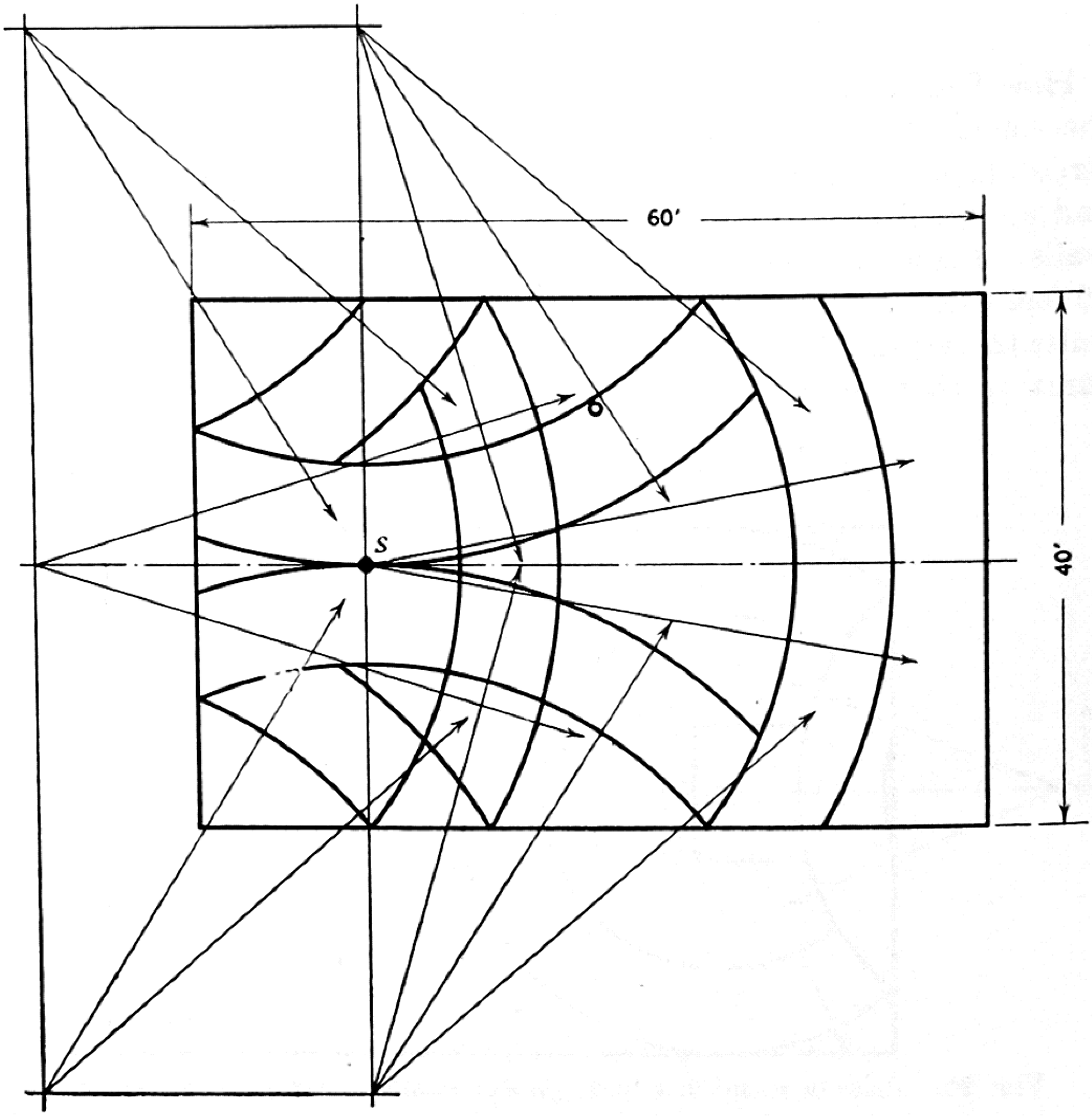

Fig. 2*b*. Pulse of sound, $\frac{2}{60}$ second after leaving the source, *S*.

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[1] Raquet and Watson, *Jour. Acous. Soc. Amer.*, Vol. 9, p. 352, 1938.

from the metal outline. These were made visible stroboscopically by flashes of light that passed up through the glass bottom of the tank and cast a shadow of the waves on the frosted glass above the water. Figure 2*d* pictures the arrangement. The puffs of air and the flashes of light are regulated by the holes in the rotating wheel. These water waves are quite similar in their action to sound waves and give a convenient means for studying the acoustic effect of proposed architectural features in auditoriums so that objectionable constructions may be redesigned before the final plans are completed. Moving pictures of these waves have been taken to show in detail their progression and reflection.

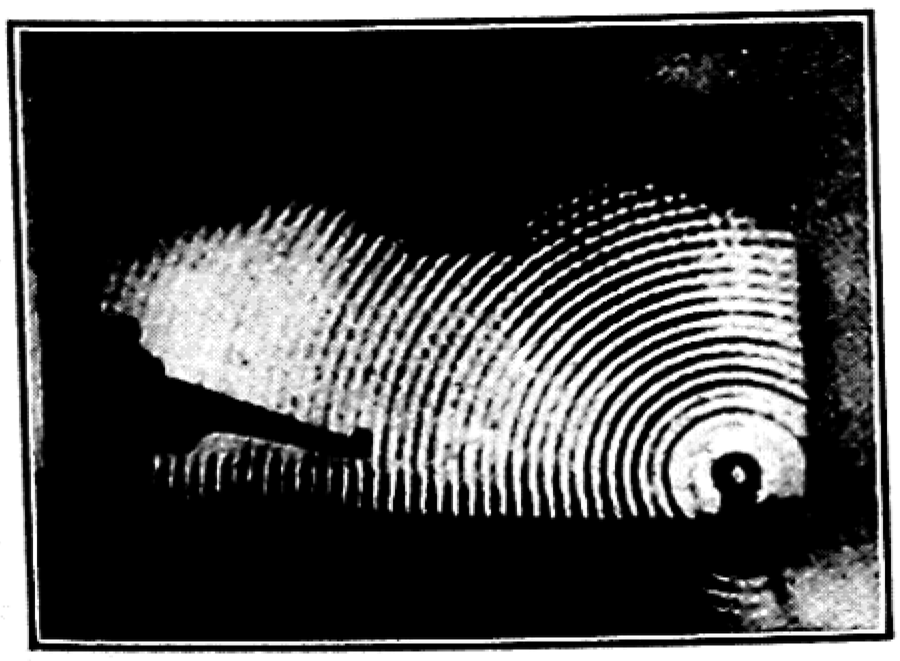

Fig. 2*c*. Photograph showing how sound waves are set up in an auditorium.

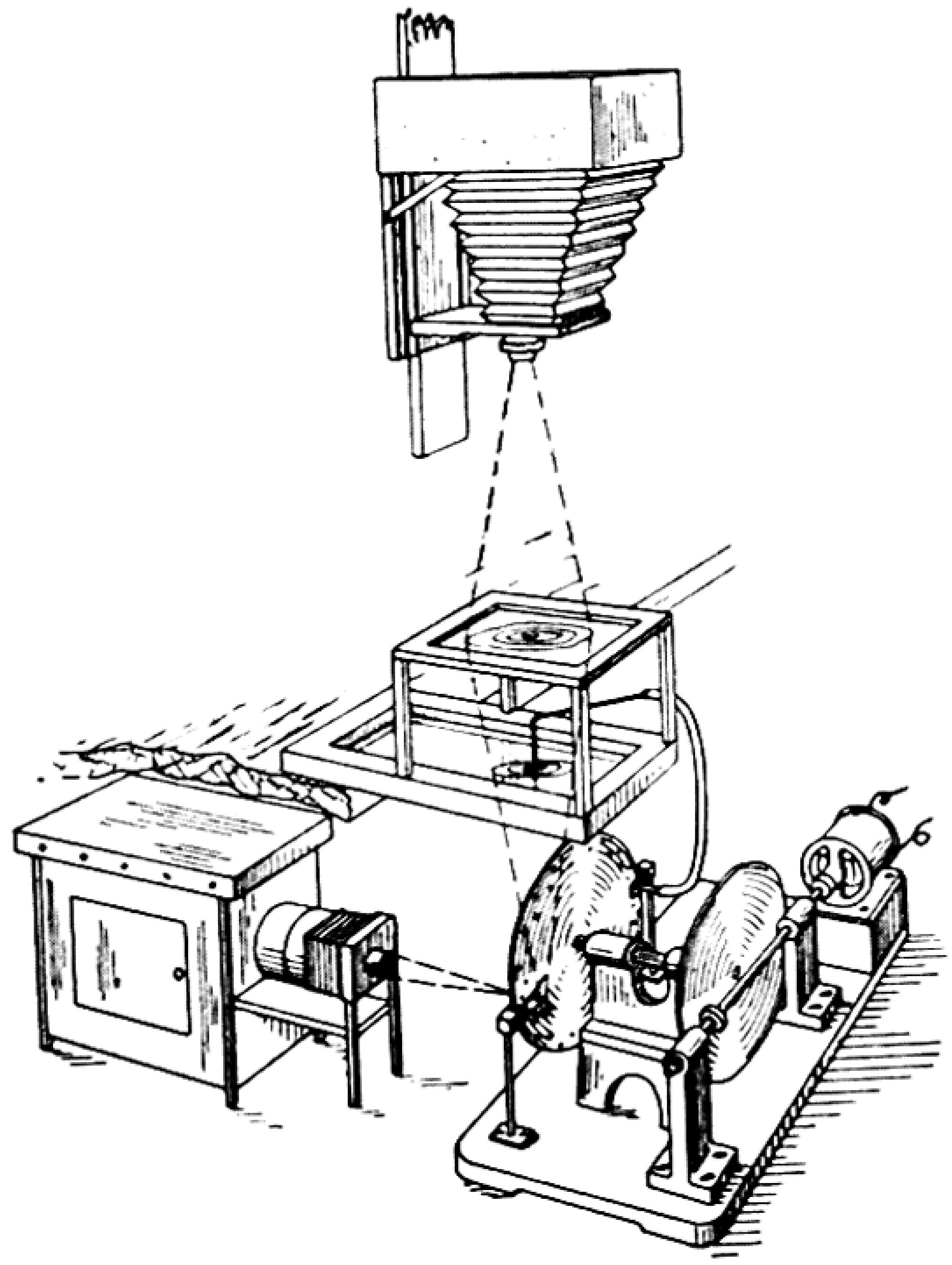

Fig. 2*d*. Diagram of apparatus for showing waves stroboscopically.

An inspection of Figs. 2*b* and 2*c* shows how sound waves would fill a room after a considerable number of reflections, resulting in a thorough mixture, practically the so-called " diffuse " sound, for which, at each point in the room, there is an equal flow of sound in every direction. This random motion of the sound waves, just described, is modified by the amplification of the " natural " or " normal " modes of vibration. For example, reflections of sound between parallel walls, or between floor and ceiling, and more complicated oblique actions, will set up standing waves of sound that may become objectionable if the frequency of the original sound is such as to encourage these vibrations. That is, certain elements of a complex sound will be unduly strengthened, resulting in a distortion of the original sound. These effects will be discussed later; it is sufficient for the present to state that they become important in small rooms used for broadcasting and sound recording; but for auditoriums of usual size and shape, where the frequencies of the sound are not less than 100 cycles per second, the distortion due to the normal modes can usually be neglected, and there will result the same average loudness for all auditors, even for those in remote corners of the room.

Though the reflection of sound produces some beneficial increase in loudness, it unfortunately introduces possibilities for defective acoustics. For instance, when the walls of the room are hard and smooth, very little energy is lost at each impact, and many reflections take place before the sound finally dies out. This prolongation, or *reverberation*, as it is called, is the most common acoustic defect in auditoriums. If a speaker talks in such a hall, the auditors will have difficulty in understanding him. Sounds will persist too long, and successive words of a speech will overlap and produce confusion. The trouble is corrected by the introduction of special materials on the walls that act as absorbers and reduce the time taken for the sound to die out.

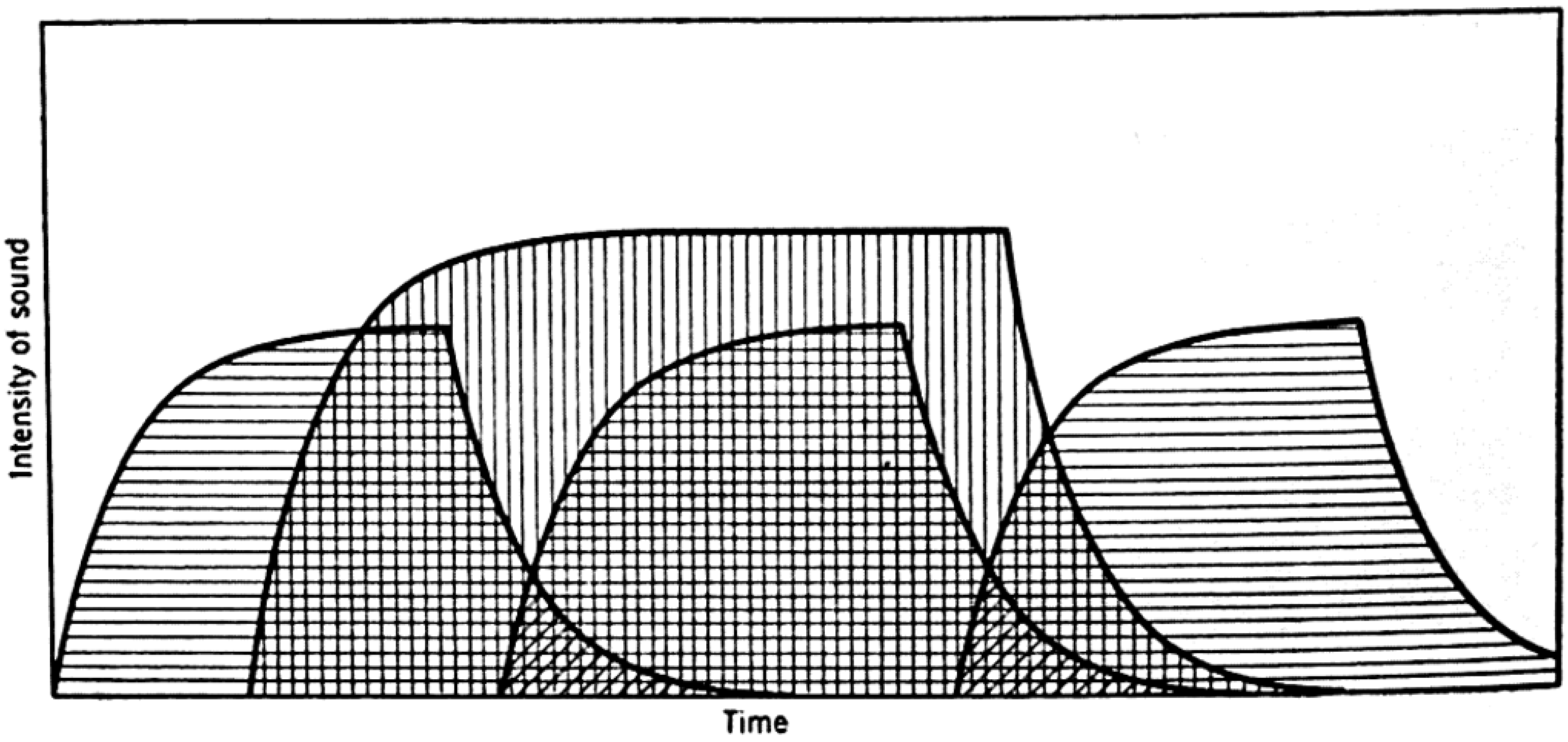

FIG. 2*e*. Diagram showing the overlapping intensities of a series of musical sounds, analogous to playing a piano with the loud pedal in use.

When music is played in an auditorium with a prolonged reverberation, the tones following one another overlap and produce the same effect as that of a piano when played with the loud pedal in use. See Fig. 2*e*. Reverberation is less objectionable for music than for speech, since the prolongation and blending of musical tones are usually desired, but the mixing of the words of a speech is a distinct disadvantage. When correcting halls used for both music and speaking, it is customary to choose an average time of reverberation that is somewhat too long for the best conditions for speech and somewhat too short for music, yet fairly satisfactory for both.

In addition to creating a reverberation, the reflection of sound sets up other actions, which are disadvantageous, namely, echoes, interference, diffraction, blurring, and resonance. Some of these phenomena have already been discussed in Chapter I, and further consideration will be given to them in later chapters, when necessary.

Conditions for Perfect Acoustics in an Auditorium. Perfect acoustic conditions in an auditorium may be expected when an average sound has a suitable loudness for all the auditors, with no echoes or distortions of the original sound, and when it dies out quickly enough so as not to interfere with succeeding sounds. These ideal conditions are seldom found in auditoriums. Reflections of sound from the walls set up distortions and unequal loudness in different parts of the room, thus making it impossible, except with special arrangements, to secure simultaneously the ideal conditions for suitable loudness and an acceptable time of reverberation. Fortunately, a considerable departure from the ideal is not objectionable for the average auditor, so that any auditorium of usual size and shape may be treated so as to acquire properties that will be generally satisfactory.

CHAPTER III

HOW SOUND BUILDS UP AND DIES OUT IN A ROOM

Acoustical Images. Figures 2*a* and 2*b* have shown how a pulse of sound is reflected from the surfaces of a room. It is now desirable to consider these reflections in greater detail, using a continuous sound instead of a pulse. Thus, in Fig. 3*a*, sound reaches the auditor *A* first directly from the source, then by reflection from the wall *RQ* as if it came from the acoustic image S_1, which is located at a point which is the same distance back of the wall *RQ* as the source is in front of it.

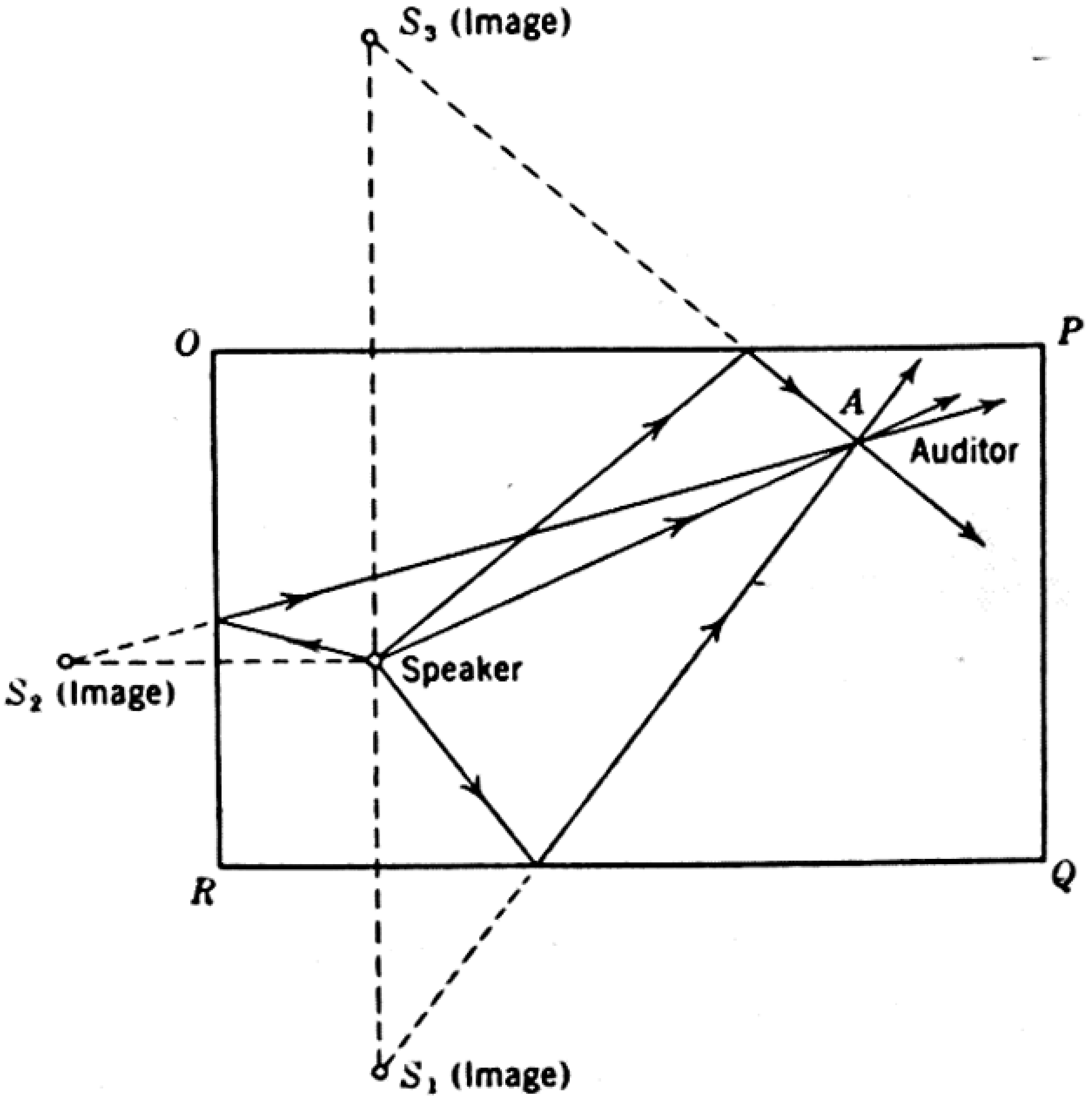

FIG. 3*a*. Acoustic images set up by reflection of sound from the walls of a room.

In the same manner, sound comes from the images S_2 and S_3. Figure 3*b* shows how a sound is reflected *twice* before reaching the auditor. Starting from the source *S*, this sound is reflected at *B* as if coming from the image S_1; it is then reflected at *C* as if coming from the point S_4, which is the image of S_1 as " mirrored " in the wall *OP*.

From the illustrations in Figs. 3*a* and 3*b*, the reader can picture more complicated reflections, with many images located at increasing distances from the source. In a room with highly reflecting surfaces, it is possible to get several hundred such reflections before the room is filled with sound. It should be remembered that the sound waves are weakened because they spread out in spheres, as shown in Figs. 2*a* and 2*b*; also, that some energy is absorbed at each reflection, so that finally the waves become so faint that they cannot be heard by the auditor.

By means of this conception of images, the actual sound heard by the auditor may be pictured by the following suggestive device. First, locate all the images of the source of sound and the images of the walls of the room, such as *R′Q′* in Fig. 3*b*. Then, at a certain instant, imagine the same sound to start simultaneously from the source and all the images, each one emitting the same amount of energy. The auditor will get sound first from the source, then from the nearby images, then from those further removed, and finally the faintest sound he can detect from the most distant images. In this conception, remember that the sound is weakened by spreading out in spheres and that a fraction of the energy is absorbed every time it passes through a mirrored wall, such as *R′Q′* in Fig. 3*b*, where the energy "absorbed" is equal to the energy actually absorbed by reflection at the wall *RQ*.

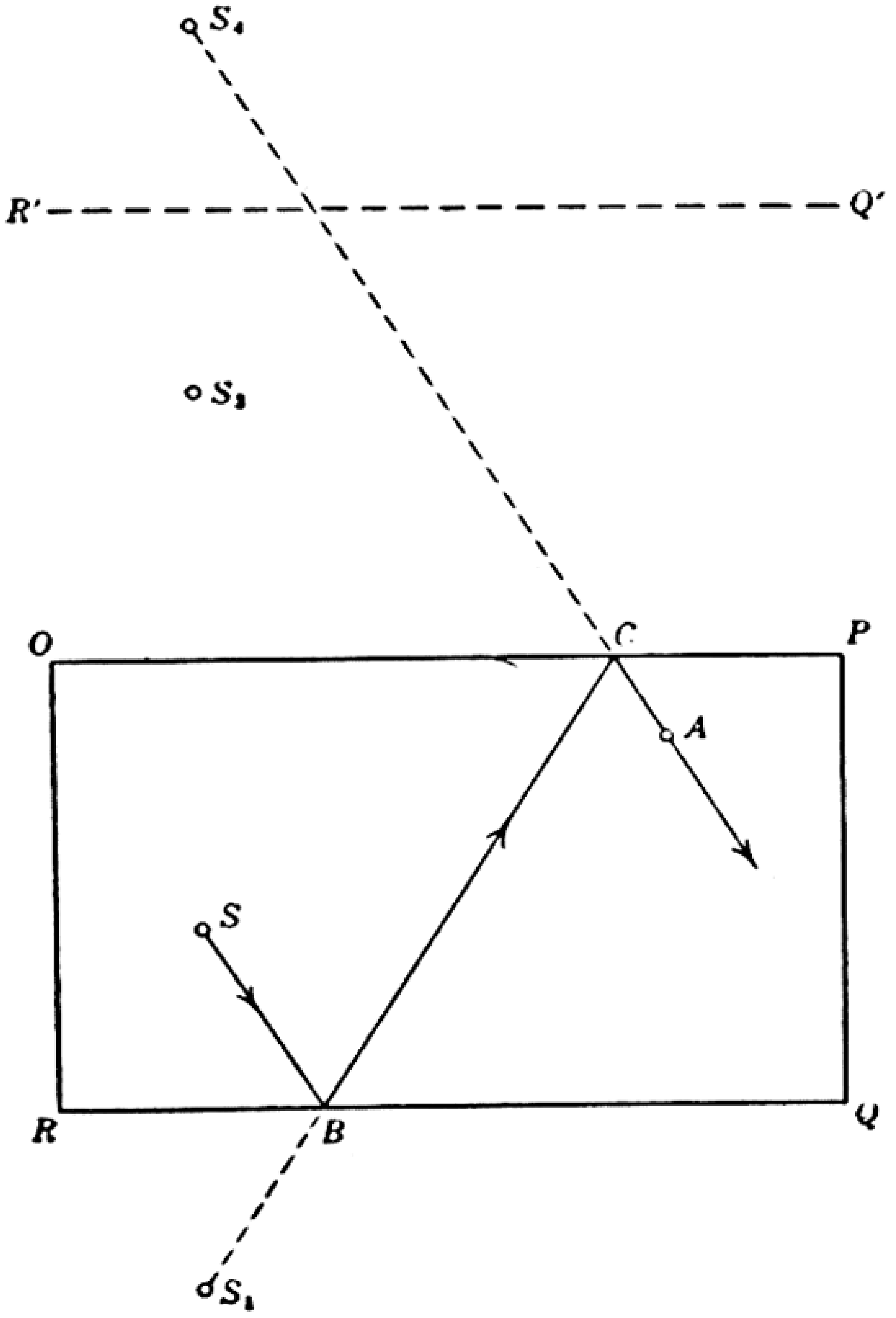

FIG. 3*b*. Diagram showing how sound is reflected twice at the walls of a room.

It thus appears that the auditor does not get a steady stream of sound, but a series of intermittent sounds that come one after another to build up the total effect, or steady state, in which just as much sound is absorbed by the walls as is emitted by the source. Figure 3*c* pictures the beginning of this action. Suppose that the sound starts from a speaker at a time $t = 0$, and reaches the auditor in a short time t_1, thus giving him a steady stream of sound of intensity t_1A; then a short instant later he gets a second stream of intensity *BC* from the direction S_1A shown in Fig. 3*a*; then a stream of intensity *DE* from the direction

S_2A; etc. The actual effect is not as sharply discontinuous as shown in Fig. 3*c* because speech sounds require a short time to build up and the auditor would not get the full intensity at once. Furthermore, the time interval between successive sounds is usually so short that the ear does not perceive them separately. The dotted line therefore suggests the average effect received by the ear.

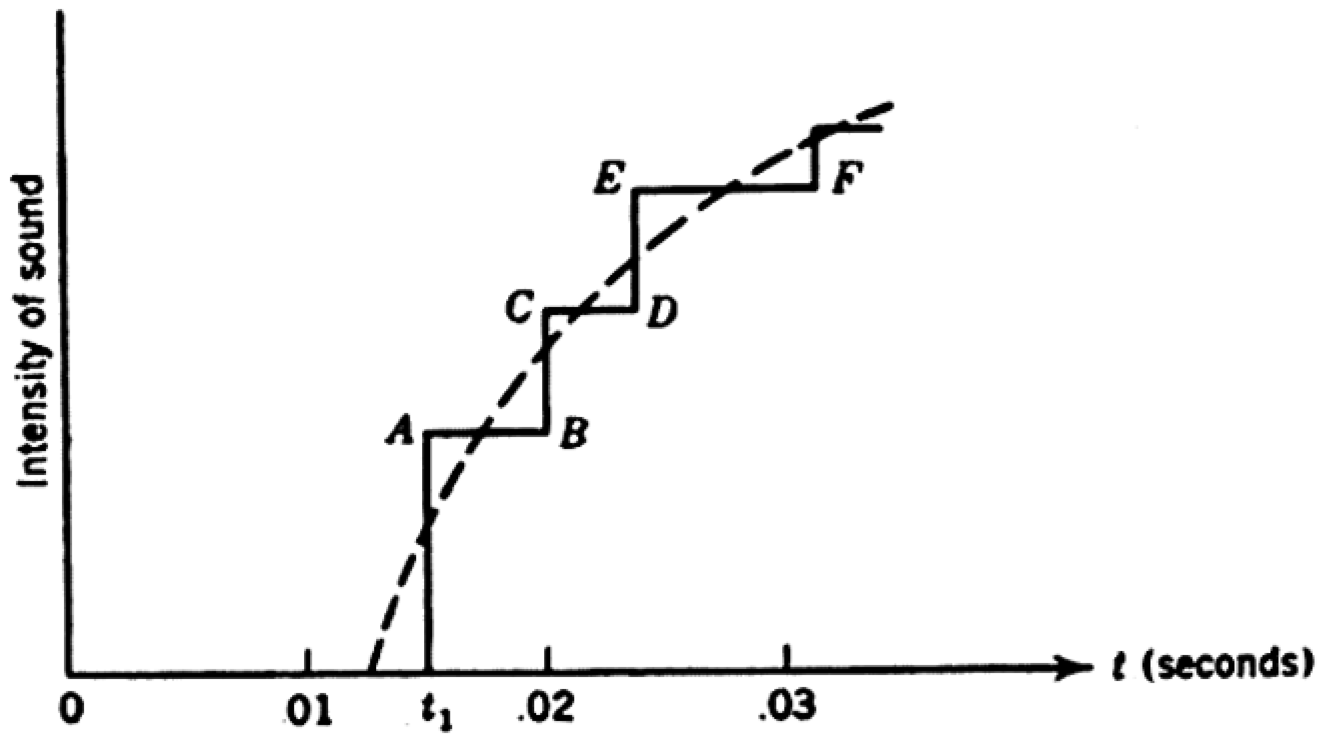

FIG. 3*c*. Pulses of sound reaching an auditor directly from the source and by reflection from the walls.

Consider now the reverse process when the sound in a room dies out. That is, imagine that the source of sound and all the images are "pouring" sound into the auditor's ears so that he is getting the full effect, when suddenly they all stop emitting sound. The auditor would first lose the stream of sound coming directly from the source, then the sound from the nearest image, and so on until the last faint sound

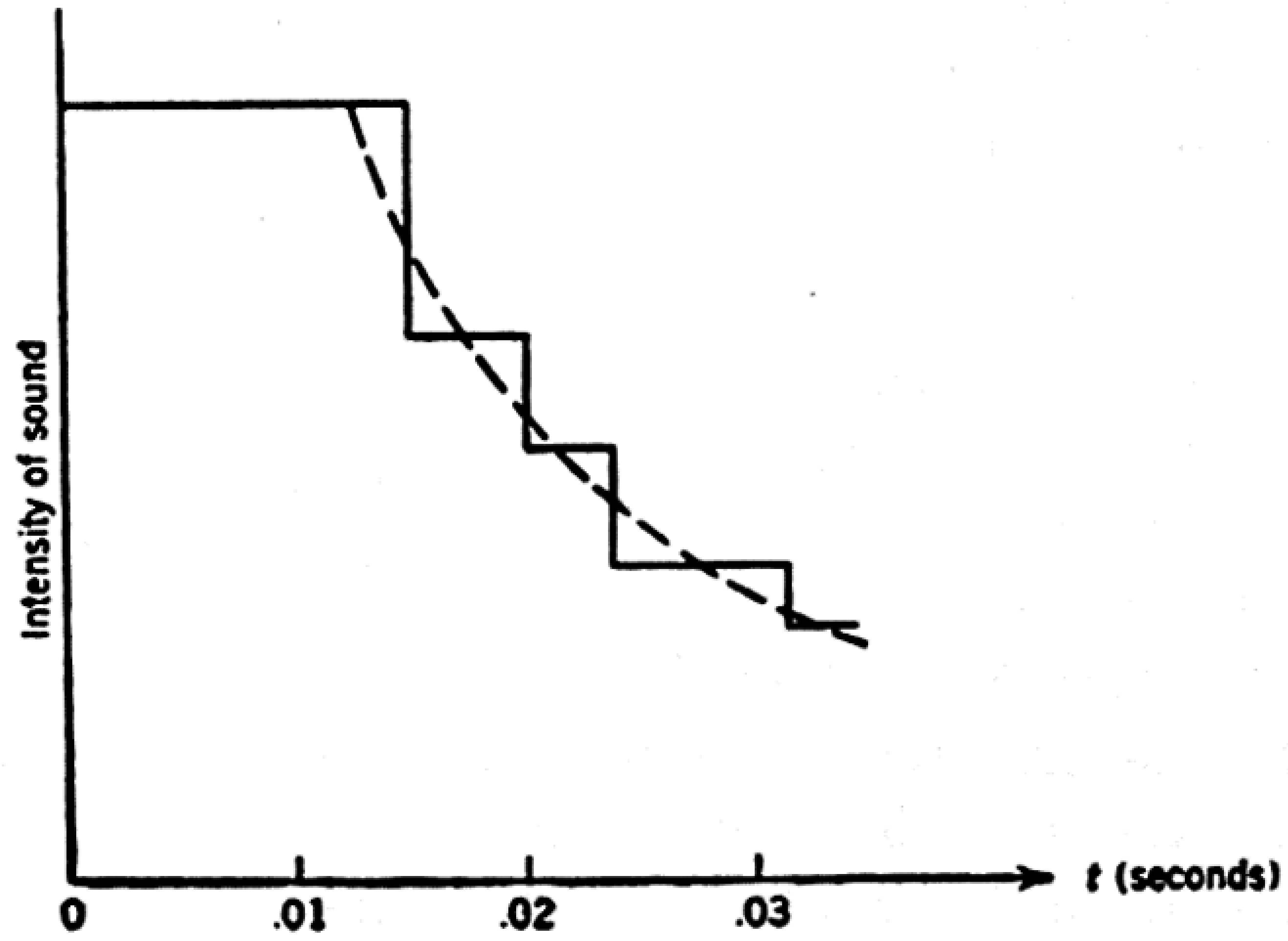

FIG. 3*d*. Diagram showing how sound falls off intermittently at the position of an auditor.

arrives from the most distant image. This decay of sound is shown in Fig. 3*d*, in which the curve is the same as the one in Fig. 3*c*, but upside down.

The four figures on the following page illustrate graphically the decay of sound in an actual room.

Normal Modes of Vibration. The preceding discussion showing the action of the first few reflections of sound is very important in estimating beneficial sound and in revealing possible echoes in a room. The time taken for these first reflections is only a small fraction of a second. As time goes on, the reflections increase and the sound becomes more thoroughly mixed. However, it appears that some streams of sound in certain directions become strengthened by continued reflections and are unduly louder than other sounds. These resonances are noticeable in small rooms, as for instance in bathrooms which have highly reflecting walls. In broadcasting rooms, these resonances present a serious problem since they distort the " high fidelity " of sounds by making certain components too loud.

The equation for the frequencies, f, of these " normal modes," as they are called, is as follows:

$$f = \frac{c}{2}\left[\left(\frac{p}{l}\right)^2 + \left(\frac{q}{w}\right)^2 + \left(\frac{r}{h}\right)^2\right]^{1/2}$$

where p, q, and r are numbers, 0, 1, 2, 3, etc., for different modes; l, w, and h are respectively the length, width, and height of the room; and c is the velocity of sound. As an example, if $q = 0$, $r = 0$, then $f = cp/(2l)$, which gives the normal vibrations parallel to the length of the room. If the length of the room is 10 feet, the velocity of sound 1,120 feet per second, and $p = 1$, then $f = 1{,}120/(2 \times 10) = 56$ cycles per second. For $p = 2$, $f = 112$ cycles per second, etc. Similar vibrations can be set up parallel to the width and height of the room. Diagonal vibrations can also take place, as, for example, when $p = 1$, $q = 1$, and $r = 0$.[1]

How to Reduce Normal Modes. To reduce these vibrations, it is necessary to install absorbing material on three adjoining surfaces of a room so as to affect length, width, and height vibrations. The practice of installing absorbing material only on the ceiling of a room is thus seen to be insufficient, since it will affect principally the vertical reflections between the floor and ceiling and will not directly reduce the horizontal vibrations. In auditoriums, it would appear better tc treat the side walls before considering the ceiling, because the audience

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[1] For details, consult Morse, *Vibrations and Sound.*

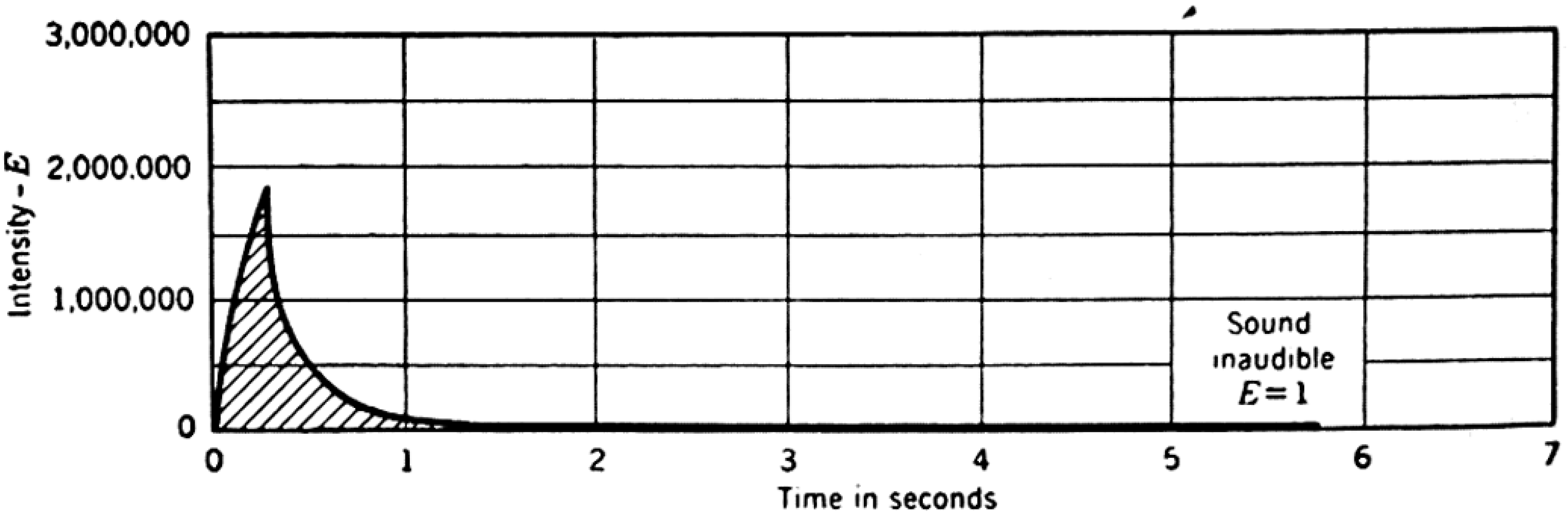

FIG. 3e. The intensity of a spoken word rises rapidly in a room and dies out slowly.

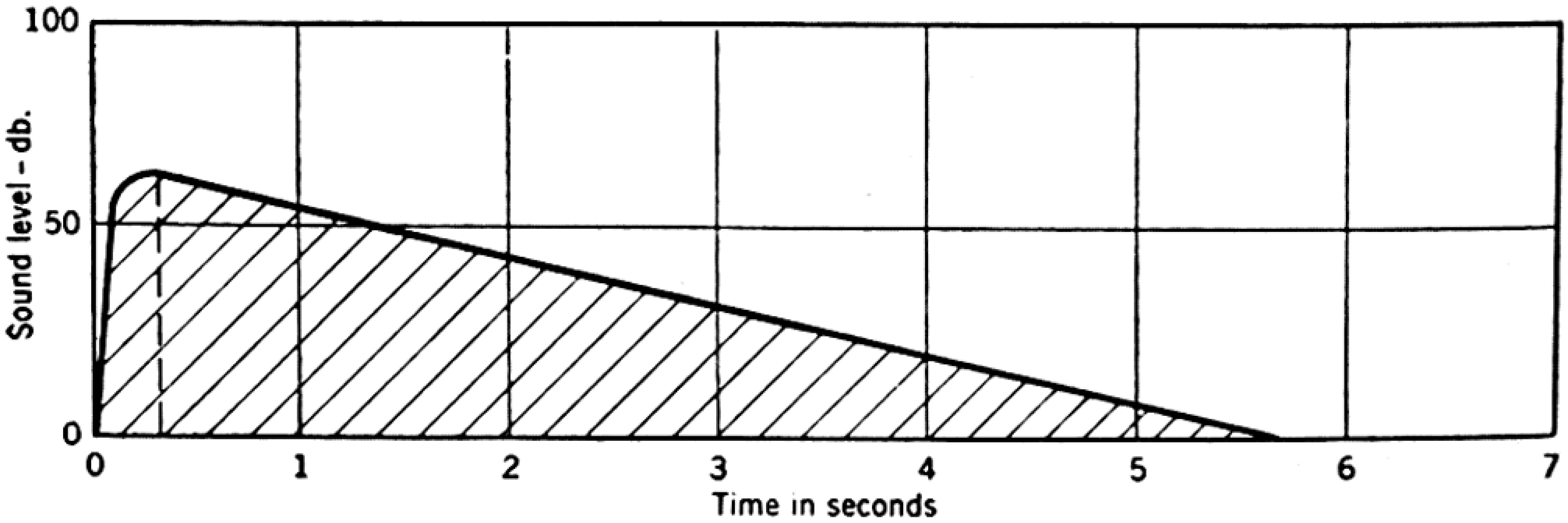

FIG. 3f. Graph showing the intensity curve of Fig. 3e in decibels; it corresponds more nearly to what the ear perceives.

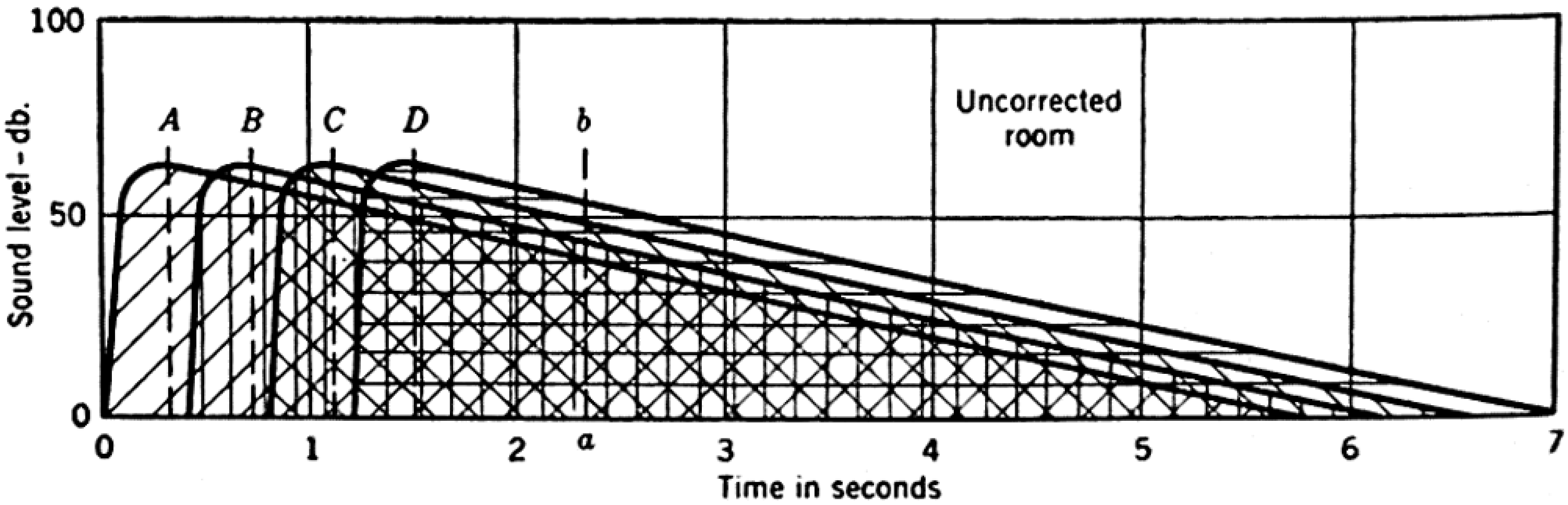

FIG. 3g. Diagram showing the overlapping of four successive words of a speech in a reverberant room.

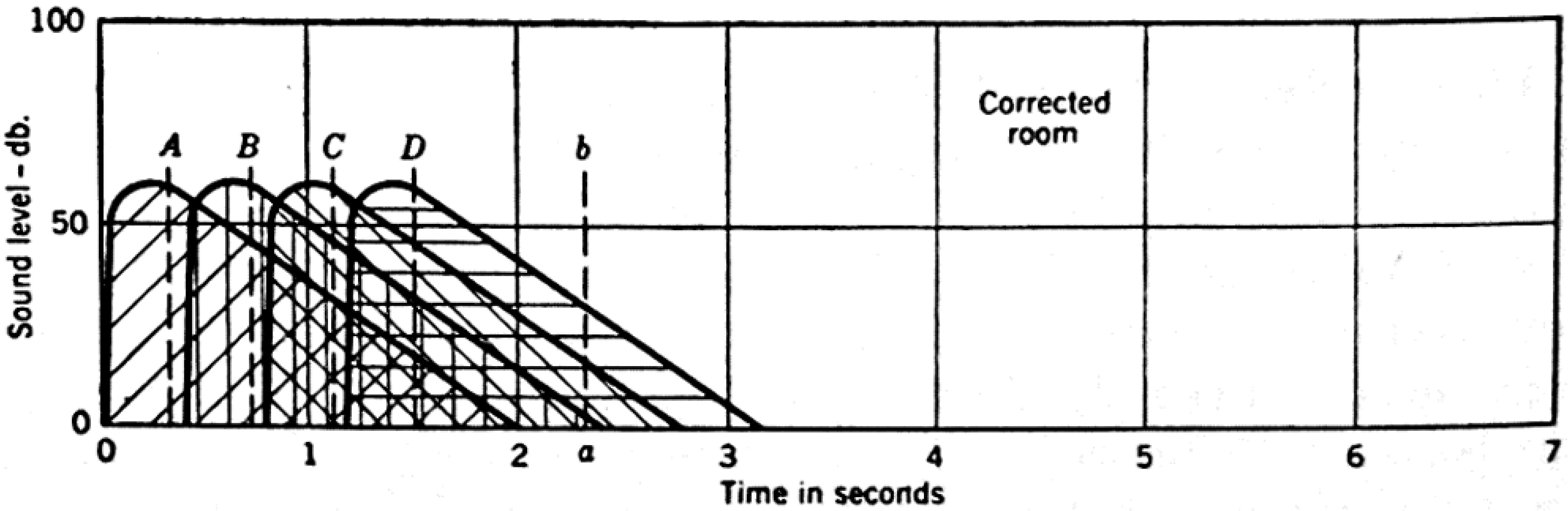

FIG. 3h. Beneficial reduction in the overlap of the sounds shown in Fig. 3g when the room is corrected by the installation of absorbing material.

and seats will present more or less absorption for the vertical motions, but there is usually no efficient absorption for the horizontal motions. The acoustic correction of rooms requires a consideration of these normal modes with an intelligent placing of absorbing materials to control them. According to the theory of these vibrations, it is surprising to learn that the positions in a room for most effective absorption of sound are the corners and along the edges.

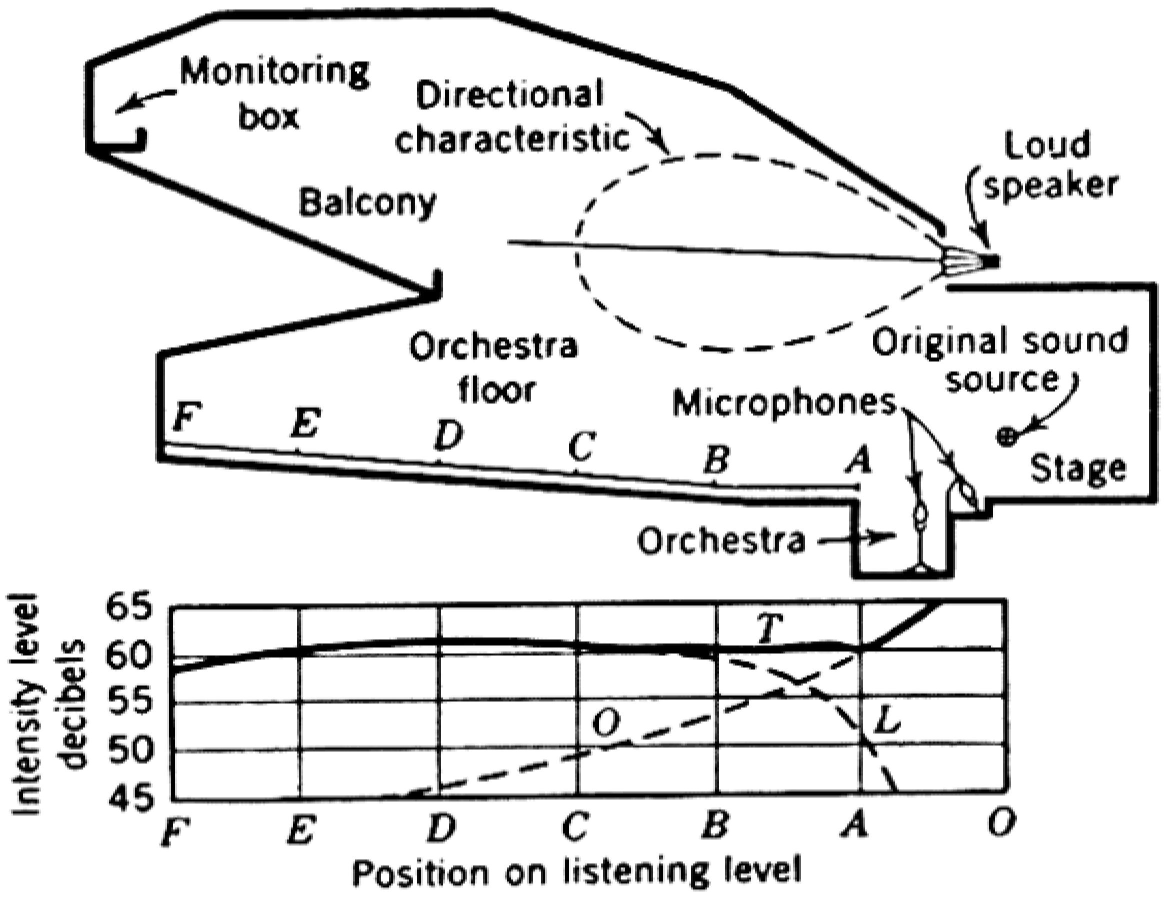

FIG. 3*i*. Arrangement of the components of a sound-reinforcing system in a theater. The graph shows the intensity levels of sound at the positions *A*, *B*, *C*, *D*, *E*, and *F* on the orchestra floor. Curve *O* gives the intensity level due to the unaided source of sound, while curve *L* shows the reinforced intensity from the loud-speaker, and curve *T* represents the resultant level of the two sources. Note that the resultant level is almost uniform over the entire floor. (From H. F. Olson, *Elements of Acoustical Engineering*. Courtesy of D. Van Nostrand Company, Inc.)

Public-Address Systems. A very important new development in the acoustics of rooms has been brought about by the use of public-address systems, or sound-amplifying systems. These consist of a microphone that "picks up" the sound and converts the sound energy into an electric current, which is amplified and reconverted back into a louder sound that is emitted from a loud-speaker directly to the audience.

Thus, instead of the comparatively weak sound of a speaker's voice that spreads out in spherical waves, the loud-speaker emits a powerful beam of sound that is sent directly to the audience. This arrangement is comparable to the action of an auto headlight on a foggy day. The loud-speaker is like an acoustic headlight that pierces the "fog" of reverberant sound in the room and concentrates loud sounds on the auditor, thus allowing him to "see" (hear) the sound. A suitable sound-amplifying system allows all the auditors in the room to hear easily, those in the rear seats getting just as loud sounds as those in the front seats near the speaker. The system also raises the general sound level, which tends to hold the attention of listeners more effectively than the usual weaker sounds of speaking — a feature that is welcomed particularly by the hard of hearing. Figure 3*i* portrays a typical auditorium showing how an even distribution of sound can be set up when an amplifying system is used to build up the sound in the rear parts of the room. Note that the sound level has the acceptable value of 60 db.

The use of public-address systems introduces a new problem in acoustic control. That is, while a large part of the energy of the beam of sound from the loud-speaker is absorbed by the audience (clothing and seats), it is necessary to make provision for the drastic reduction of the reflection from the rear walls, if echoes and other sound concentrations are to be avoided. This control is brought about by designing the rear walls so that regular reflection and concentration of sound are reduced, and by installing special sound-absorbing constructions.

CHAPTER IV

REVERBERATION EQUATIONS

(*This chapter may be omitted on first reading.*)

Preliminary View. Suppose that sound has been built up in a room, as explained in Chapter III, until a steady state exists in which the sound energy is absorbed as fast as the source supplies it. Then consider the decay of sound when the source is suddenly stopped. The element of sound E_0, Fig. 4*a*, strikes the wall at *A* where an absorption of, say, 3 per cent takes place. The sound is thus reduced from E_0 to $E_0 - 0.03\,E_0 = (1 - 0.03)\,E_0 = 0.97\,E_0$, so that $0.97\,E_0$ is reflected. On striking a second wall at *B*, another 3 per cent is absorbed and the amount reflected is $0.97 \times (0.97\,E_0)$ or $(0.97)^2\,E_0$. After the third reflection, the sound is reduced to an energy $E_3 = (0.97)^3\,E_0$, and so on until, after *n* reflections, the reduced energy becomes $E_n = (0.97)^n\,E_0$. Suppose after *n* reflections that the initial sound E_0 has been reduced to one-millionth of its original value, or $E_n = 0.000001\,E_0$. Then the number of reflections *n* required to bring about this reduction is given by the equation: $E_n = (0.97)^n\,E_0 = 0.000001\,E_0$, from which *n* is found to be 461 reflections. That is, in a room for which the absorption of sound at the walls is 3 per cent, there would be 461 reflections of sound for the energy to decrease to one-millionth of its initial value.

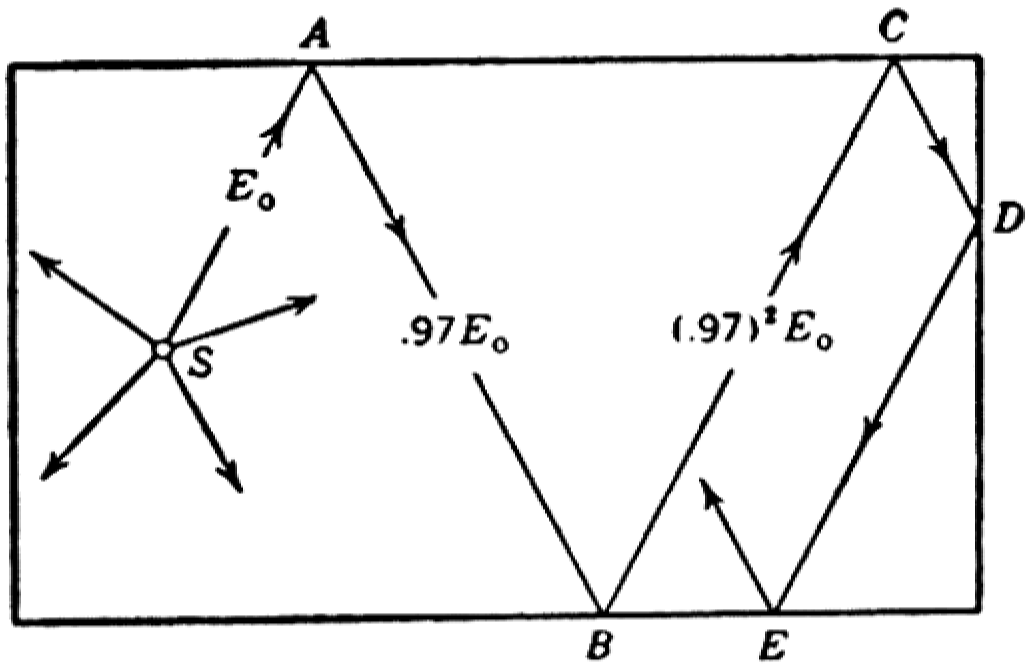

FIG. 4*a*. Diagram showing successive reflections of sound in a room, with values of the intensities after reduction by a 3 per cent absorption at each reflection.

Mean Free Path. Inspection of Fig. 4*a* shows that the distances between successive reflections, *AB, BC, CD, DE,* etc., are not equal, but if a large number of these distances is averaged, the result is called the *mean free path,* which is the average distance between successive reflections. An equation by means of which a value for the average may be calculated has been developed as follows: $p = 4V/S$, where *p* is the mean free path value, V is the volume of the room, and S is the area of all the interior surfaces of the room. For example, in a room of 100,000-cubic-foot volume and with an interior surface area of 20,000 square feet, the mean free path is $p = 4 \times 100{,}000/20{,}000 = 20$ feet.

More General Case. The consideration of a single element of sound pictured in Fig. 4*a* can be extended as an average to include all the elements of the spherical wave leaving the source S, each small element experiencing the same absorption of 3 per cent at each reflection and requiring 461 reflections to decrease to one-millionth of its initial value; and having the mean free path of $4V/S$.

Time of Reverberation. The values just presented allow a calculation to be made for the time of reverberation, that is, the time taken for a sound to decrease to one-millionth of its initial value. Thus in the room of 100,000-cubic-foot volume, in which the average distance between successive reflections (mean free path) is 20 feet, the distance traveled by the sound in making 461 reflections would be 20 × 461, or 9,220 feet. The time taken to travel this distance, taking the velocity of sound as 1,120 feet per second, is found to be: $9{,}220 \div 1{,}120 = 8.22$ seconds. This time is entirely too long for good acoustics and indicates what is to be expected in a room lined with hard plaster, wood, and glass for which the absorbing values are about 3 per cent, assuming the values of the volume and area of the room to be 100,000 and 20,000 respectively. In smaller rooms, the 461 reflections would be completed in a shorter time, because the walls are closer together and the mean free path would have a smaller value; in larger rooms, the opposite would be true and the time of reverberation would be longer. In all three cases, however, the time would be too long and the acoustics would be unsatisfactory. If absorbing materials were installed, so that the average absorption for each reflection were increased to 20 per cent, the time of reverberation for 100,000-cubic-foot volume room would be reduced to 1.105 seconds, a satisfactory solution for reverberation.

Normal Modes. The discussion just given does not apply to all rooms. For example, particularly in small rooms, certain elements of the spherical wave are encouraged more than others and the normal modes become prominent, as explained in Chapter III. As a result, the condition of " diffuse sound," in which at any point in the room the flow of sound is the same in all directions, is not fulfilled as required in the development of the equation for the mean free path. However, for large rooms and for sounds whose frequency is not too low, the diffuse condition is sufficiently approximated and the equations just developed can be used for acoustic correction calculations.

Reverberation Equations. Using the relations discussed in the preceding paragraphs, and substituting α for numerical value of the absorption, it may be shown that the time of reverberation may be expressed by the equation:

$$t = \frac{0.05V}{vS[-\log_e (1 - \alpha)]}$$

which is the so-called Eyring equation. If the value of α is less than about 0.2, then $[-\log_e (1 - \alpha)]$ may be replaced by α and there results the usual Sabine equation: $t = 0.05V/(\alpha S)$. See Table 4*a*. The Sabine equation is commonly used when calculating the amount of absorbing material needed to correct the reverberation, unless there is an unusual amount of absorption, in which case the Eyring equation is employed.

TABLE 4*a*

VALUES OF α AND $-\log_e (1 - \alpha)$

α	$-\log_e (1 - \alpha)$	% difference
0.05	0.051	2.0
0.10	0.105	5.0
0.20	0.223	11.5
0.30	0.357	19.0
0.40	0.511	27.8
0.50	0.693	38.6

Derivation of the Eyring Equation.[1] Using the equation given at the beginning of this chapter and substituting α for the absorption coefficient 0.03, we have $E = E_0 (1 - \alpha)^n$, or $E_0/E = (1 - \alpha)^{-n}$. Taking logarithms and solving for n,

$$n = \frac{\log_e \left(\frac{E_0}{E}\right)}{[-\log_e (1 - \alpha)]} = \frac{2.3 \log_{10}\left(\frac{E_0}{E}\right)}{[-\log_e (1 - \alpha)]}$$

The value of n may be found from the relations used earlier in the chapter: $np = vt$, or $n = vt/p = vtS/4V$. n = number of reflections for the sound to decrease from E_0 to one-millionth of E_0.

$p = 4V/S$, or the mean free path.
v = velocity of sound, 1,120 feet per second.
t = time taken for E_0 to decrease to one-millionth of its value.

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[1] R. F. Norris, *Jour. Acous. Soc. Amer.,* Vol. 3, p. 361, 1932.

Taking E_0/E equal to $10^6/1$, and equating the two equations for n:

$$n = \frac{vTS}{4V} = \frac{2.3 \times 6}{-\log_e (1 - \alpha)]}$$

Solving for t:

$$t = \frac{4 \times 2.3 \times 6}{1{,}120} \frac{V}{S[-\log_e (1 - \alpha)]} \quad \text{(Eyring's equation)}$$

If $[-\log_e (1 - \alpha)] = \alpha$, approximately, t reduces to $0.05\, V/\alpha S$ (Sabine's equation).

General Form of Reverberation Equations. The decay of sound in a room may be expressed in a more general equation: $E = E_0\, e^{-bt}$, where E_0 is the original energy of the sound, E is the reduced energy t seconds after the emission of sound is stopped, and b is a factor depending on the assumptions made.

A. Sabine's equation:[1] $b = v\alpha S/4V$.

v = velocity of sound.
S = total surface area of the room.
V = volume of the room.
α = average absorption coefficient = $\sum (\alpha_i S_i)/S$.
S_i = area of the room surface having the absorptivity α_i.

Assumptions:

1. Rate of change of energy density is a continuous function of time. (This is approximately true for " live " rooms.)
2. Uniform directional distribution of energy flow at every point in room. (This is approximately true when a large number of natural frequencies of room are excited.)

B. Eyring's equation:[2]

$$b = -\frac{vS \log_e (1 - \alpha)}{4V}$$

Assumptions:

1. At each reflection the sound energy is reduced to $(1 - \alpha)$ times its original value, where α is the average absorptivity. This presupposes uniform distribution of energy at each incidence. (This is approximately true when a large number of the natural frequencies of the room are excited.)

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[1] W. C. Sabine, *Collected Papers on Acoustics*, Cambridge Press, 1922.

[2] C. F. Eyring, *Jour. Acous. Soc. Amer.*, Vol. 1, p. 217, 1930.

C. Millington's equation:[1]

$$b = -\frac{v\sum S_i \log (1 - \alpha_i)}{4V}$$

Assumptions:

1. Specular reflection. (Approximately true when reflecting surfaces are large compared with wavelength of sound.)

2. Any ray of sound after repeated reflections will have struck any one surface area in proportion to the ratio of that surface area to the total surface area. (Approximately true when every ray of sound undergoes large number of reflections before its intensity is reduced by 60 db.)

Note: None of the above takes into account geometry of room or placement of absorbing material, source, or transmitter.

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[1] G. Millington, *Jour. Acous. Soc. Amer.*, Vol. 4, p. 69, 1932.

CHAPTER V

REVERBERATION IN A ROOM AND ITS CONTROL

Introduction. The reverberation, or prolongation of sound, is the most usual acoustic defect in auditoriums. It is a common observation that the reverberations so noticeable in an empty house disappear when the house is furnished. So in an auditorium, the reverberation is reduced when furnishings and absorbing materials are installed in sufficient amounts.

The reason for the reduction is found when we inquire what becomes of the sound. Sound is a form of energy and, as such, cannot be destroyed; but it can be changed to some other form of energy and thus disappear as sound. For example, sound waves striking the walls of a room may be converted into mechanical energy if the walls are set in vibration. Most of the energy, according to Lord Rayleigh,[1] is transformed by friction into heat. A high-pitched sound, such as a hiss, is damped out by friction in the air in traveling a short distance of about 200 feet. This action is usually disregarded in auditorium acoustics for sounds with frequencies below about 2,000 cycles. On striking the walls of a room, sound waves experience a friction in the process of reflection between the air particles and the wall, but the amount of energy thus lost is small if the walls are rigid and smooth. The case is much different for a porous surface, since it appears that friction in the pores dissipates the sound energy into heat. In this connection, Lamb[2] writes: "In a sufficiently narrow tube the waves are rapidly stifled, the mechanical energy being of course converted into heat. . . . The interstices in hangings and curtains act in a similar manner, and it is to this cause that the effect of such appliances in deadening echoes is to be ascribed, a certain proportion of the energy being lost at each reflection." Any mechanical breaking up of the sound by relief work on the walls, by obstacles in the room, or by sounding boards will not be effective in diminishing the energy of the sound. These may break up the regular reflection and reduce echoes, but the sound energy as such disappears only when friction is set up. The following quotation from Rayleigh[1] emphasizes these conclusions: "In large spaces bounded by non-porous walls, roof and floor, and with few windows, a prolonged resonance seems inevitable. The mitigating influence of thick carpets in such cases is well known. The application of similar material to the walls and roof appears to offer the best chance of further improvement."

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[1] *Theory of Sound,* Vol. II, pp. 316, 351.

[2] *Dynamical Theory of Sound,* p. 199.

Sabine's Work on Correction of Auditoriums. Important experimental work in applying this principle of the absorbing power of carpets, curtains, etc., in the correction of reverberation in auditoriums was done by Professor Wallace C. Sabine of Harvard University.[2] His pioneer work cleared the subject of architectural acoustics from the fog of mystery that hung over it and allowed the essential principles to be seen in the light of scientific investigation. In a series of interesting experiments extending over a period of four years, he deduced the equation: $t = 0.05\, V/as$, as explained in Chapter IV, where:

t is the time of reverberation, or the standard time taken for sound in a room to decay to one-millionth of its initial value.

V is the volume of the room in cubic feet.

The factor 0.05 involves a 60-db decay of the sound.

as is the total absorption value of the room, a being the average absorption coefficient and s the total area in square feet of all surfaces of the room. When making calculations for the reverberation, the value of as is found by taking the sum of the absorption values of the different materials in the room; that is:

$$as = a_1 s_1 \text{ (plaster)} + a_2 s_2 \text{ (wood)} + a_3 s_3 \text{ (carpet)} + \text{etc.}$$

EXAMPLE OF CORRECTION OF REVERBERATION. Consider an actual room 76.5 feet long, 59.5 feet wide, and 17.75 feet high, with a volume of 80,800 cubic feet. Suppose that the room has a wood floor, plastered walls and ceiling, and 550 wooden seats. The absorption (as) for all the materials is given in Table 5a. The coefficients quoted are for the frequency of 512 cycles; later it will be shown that the coefficients are different for different frequencies. Absorption values are given in units called "sabins." Inspection of Table 5a shows that the materials vary in absorbing value. Each square foot of wood absorbs 0.03 sabin, or 3 per cent of sound striking it; so that the area of 6,928 square feet of wood absorbs 211 sabins. The plaster is a little better than the wood in absorption, while the metal and glass are comparatively unimportant. The total absorption for the materials in the bare room is 567 sabins, or 570 in round numbers, which is sufficiently exact. The audience is an important

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[1] *Theory of Sound,* Vol. II, p. 333.

[2] *Collected Papers on Acoustics,* Harvard University Press, 1922.

TABLE 5*a*

SOUND ABSORPTION IN AN AUDITORIUM

Material	Area (s), Square Feet	Coefficient (a)	Absorption in sabins	
			(as)	Total (as)
Wood	6928	0.03	211.	
Plaster	7440	0.033	246.	
Metal	628	0.01	6.3	
Glass	408	0.025	10.2	
Seats	550	0.17	93.5	
Total absorbing value of bare room			567.	567
" " " " " " (in round numbers)				570
100 auditors		(4.17 − 0.17)*	400	970
200 "		"	800	1370
300 "		"	1200	1770
400 "		"	1600	2170
550 "		"	2200	2770

* Each auditor adds only the difference between his actual absorption (4.17) and the seat he occupies (0.17), which has already been counted. The absorption of auditors varies from 3 to 4.3, depending on the clothing worn and the type of seat occupied.

absorbing factor, because of the clothing worn. The following tabulation, Table 5*b*, gives the time of reverberation for the bare room; ($t = 0.05V/(as)$, also when various numbers of auditors are present.

TABLE 5*b*

TIMES OF REVERBERATION FOR UNCORRECTED ROOM

t, seconds	Audience
0.05 × 80,800/570 = 7.1	None
" " /970 = 4.2	100
" " /1,370 = 2.9	200
" " /1,770 = 2.3	300
" " /2,170 = 1.9	400
" " /2,770 = 1.5	550

Inspection of Table 5*b* shows that the times of reverberation vary from 7.1 seconds for the empty room to 1.5 seconds when the maximum audience is present, the absorption of the audience being due to the clothing worn. These times are too long for good acoustics, and absorbing material should be added to make the room deader. The actual amount of material needed is determined by the time of reverberation that will give the optimal conditions.

For a room of this volume, 80,800 cubic feet, the time is found from Fig. 6*b* to be 1.3 seconds when an average audience is present.

The absorption to give this time is calculated to be: $(as) = 0.05 \times 80{,}800/1.3 = 3{,}100$ sabins. Since the room already furnishes 570 sabins, and an average audience, estimated to be 200 persons, adds 800 sabins more, the amount of material to be added is: $3100 - (570 + 800) = 1{,}730$ sabins. With this addition, the absorption of the empty room will be: $1{,}730 + 570 = 2{,}300$ sabins, from which the times of reverberation with auditors present may again be calculated, the results being shown in Table 5*c*. It is to be noted that the audience now has only a small effect on the reverberation compared with the effect in the uncorrected room.

TABLE 5*c*

TIMES OF REVERBERATION FOR A CORRECTED ROOM

t, seconds	Audience
0.05 × 80,800/2,300 = 1.8	None
" " /3,100 = 1.3	200 optimum
" " /3,900 = 1.0	400
" " /4,500 = 0.90	550

The *area* of the 1,730 sabins of absorbing material to be added is found by dividing 1,730 by the coefficient of the material that will be used. As a step in the solution, the areas are calculated for three materials of coefficients of 0.40, 0.60 and 0.80 as follows:

TABLE 5*d*

Coefficient (*a*)	Area of material (1,730 ÷ *a*) square feet
0.40	4,320
0.60	2,890
0.80	2,160

The next step in the correction is to decide where the absorbing material should be installed to get the best effect. In this auditorium, because of the small height and the corresponding small area of side walls, the ceiling appears to be the logical surface on which to put the material. Later, this important consideration will be discussed in more detail. In auditoriums with high ceilings, for example, it is quite essential that side-wall treatment be provided. For the auditorium under discussion, the type of material to be selected depends on the area available for treatment. Since the area of the ceiling ($79.5 \times 59.5 = 4{,}730$ square feet) it would appear that the 0.40 coefficient material, with 4,320-square-foot area needed, would be the closest solution, but the extra 410 square feet could be added to cover the entire ceiling. This arrangement would give a little more material than called for,. but a certain " tolerance " is allowed, as explained in later chapters.

The correction for the auditorium just discussed is set forth graphically in Fig. 5*a*, which shows how the absorption of sound by the audience affects the times of reverberation for the room both when uncorrected and when corrected.

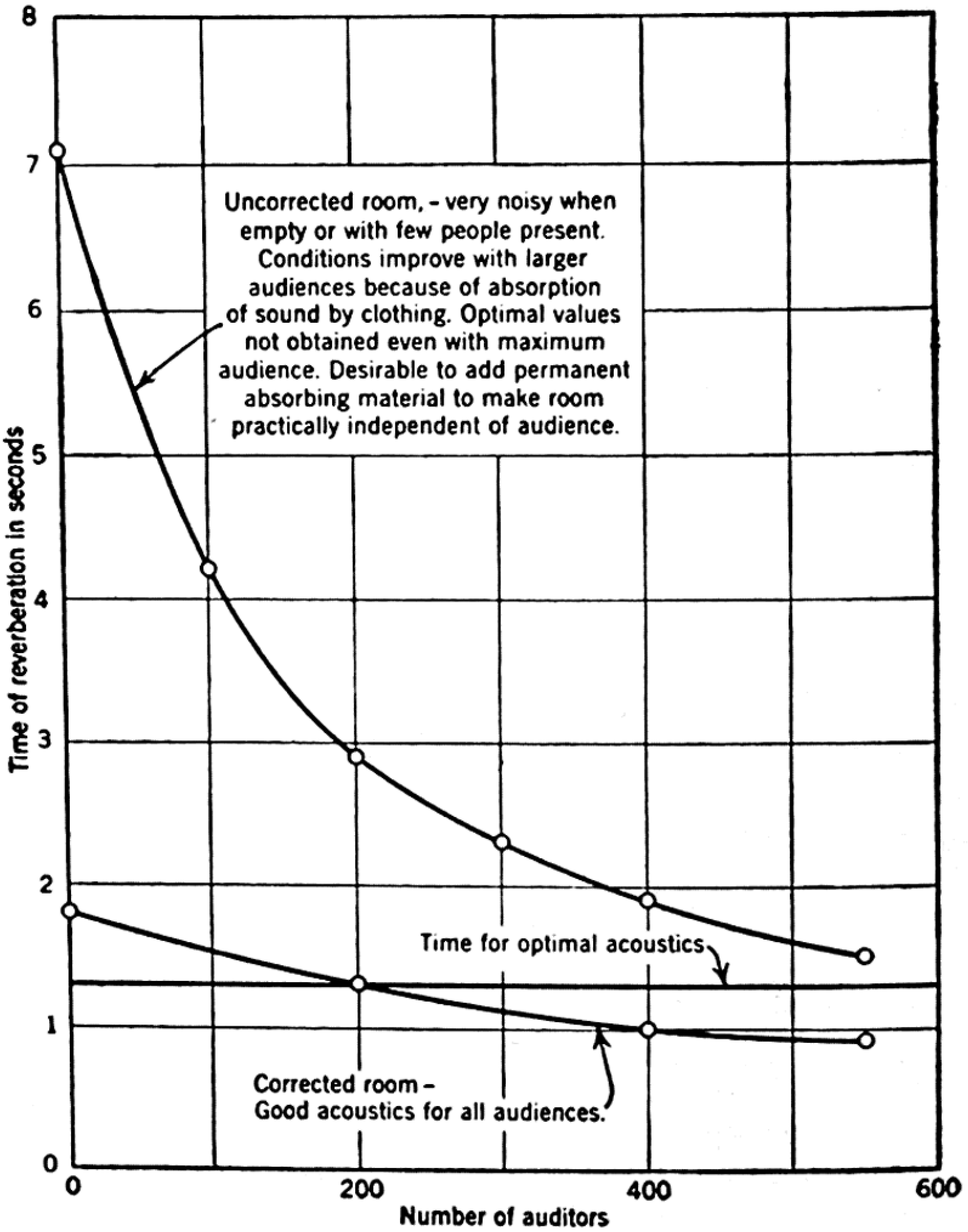

FIG. 5*a*. Graphical representation of the reduction of the time of reverberation in a room by the absorption of an audience before and after correction. Note that the corrected room is practically independent of the audience.

CHAPTER VI

OPTIMAL TIME OF REVERBERATION

Time of Sound Decay. The time taken for sound in a room to decay is a vital factor in securing good acoustics. As already explained, too long a time results in an overlap of successive speech sounds that is confusing for auditors, so that some provision is desired to hasten the decay. Just how far this procedure should go to determine satisfactory times, or optima, depends on a number of factors — the loudness of the sound; its nature, whether speech or music; the response of the ear; etc. These factors should be considered in setting up provisional optima, but the final decision rests on the opinions of listeners who decide when the resultant speech and music are satisfactory.

Optimal Times. The earliest reliable information about time of reverberation was given by W. C. Sabine[1] as about 1 second for small music studios and 2.32 seconds for the large Boston Music Hall. A general statement about the acoustic effect to be expected was given by Kreuger[2] as follows:

t, SECONDS	ACOUSTICS
Greater than 5	Very bad
Between 5 and 3	Bad
" 3 and 2	Fairly good
" 2 and 1½	Good
" 1½ and ½	Very good

These recommendations show that the acceptable time of reverberation should be *short*, but the information thus furnished was too fragmentary to provide adequate guidance for specifying times of reverberation for all auditoriums, whether new ones in the design stage or old ones that were being corrected. Figure 6a reproduces an early attempt by the author to solve the problem. It tabulates the results for a group of existing auditoriums and assumes that the data thus set forth will bring similar results if used for guidance with other auditoriums. The plotting is based on the relation that the time of reverberation varies with the cube root of the volume, which may be developed from Sabine's equation: $t = 0.05V/as$ for a spherical auditorium, but which applies very approximately for any auditorium of usual shape and size. In this figure, three curves were drawn, giving the average times for no audience, for an average audience, and for the maximum audience. These data show how an audience, because of the clothing worn, will reduce the time of reverberation. Almost any auditorium filled with a capacity audience will have good acoustics, but when empty, or with a small number of people present, will be too reverberant. It is desirable to make the room as independent as possible of the uncertainty of an audience, a condition that is brought about by the installation of the proper amount of absorbing material.

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[1] *Collected Papers on Acoustics.*

[2] "Research into Acoustical Problems in Buildings," *Ingeniors Vetenskaps Akademien*, Stockholm, 1924.

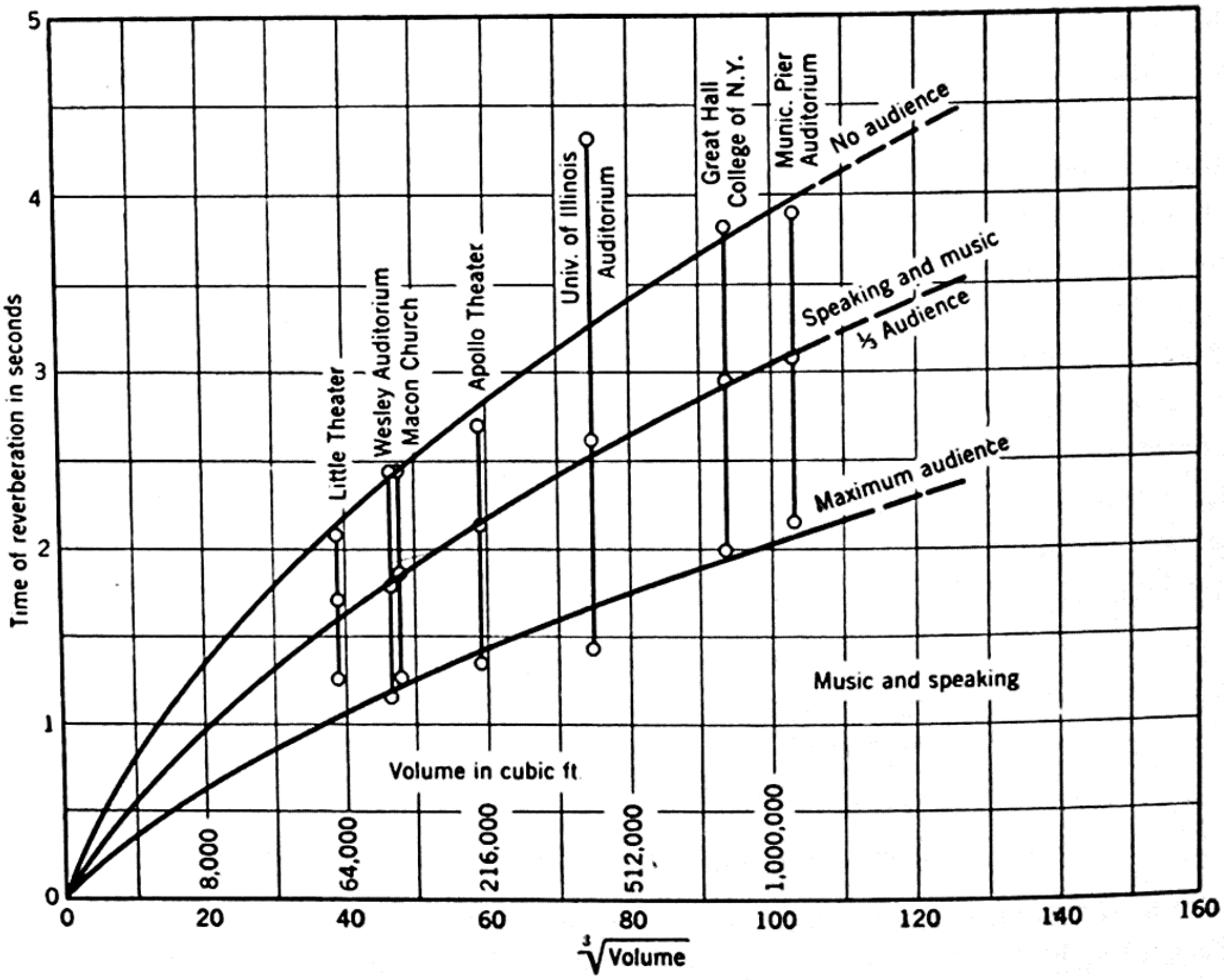

FIG. 6*a*. Graph showing an early attempt by the author to prescribe acceptable times of reverberation for auditoriums of different volumes.

Other Investigations. This problem has been studied by other investigators,[1] with the interesting development that the times of reverberation recommended became shorter and shorter, until they reached values of 1 second or less for small rooms and about 2 seconds for auditoriums with a volume of 1,000,000 cubic feet. One of the plots that has been used extensively in late years is shown in Fig. 6*b*, which gives the times of reverberation vs. volume, the volume being plotted on a logarithmic scale. The shaded region in the figure indicates the latitude in the time of reverberation allowed for different auditoriums. For sound film theaters or for auditoriums with public-address systems the time selected should be short and taken near the lower edge of the shaded part; for concert halls and churches the time should be longer and taken near the upper limit; for rooms used for both speaking and music, a middle value should be taken. The time selected should be applied to the room in question when the most probable sized audience is present.

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[1] P. E. Sabine, *Amer. Archt.*, June 18, 1924. S. Lifshitz, *Phys. Rev.*, Vol. 25, p. 391, 1925; Vol. 27, p. 618, 1926. F. R. Watson, *Architecture*, May, 1927. Beljajew, "Akustik grosser Raume," *Deutsch. Bautztg.*, No. 7, 1926.

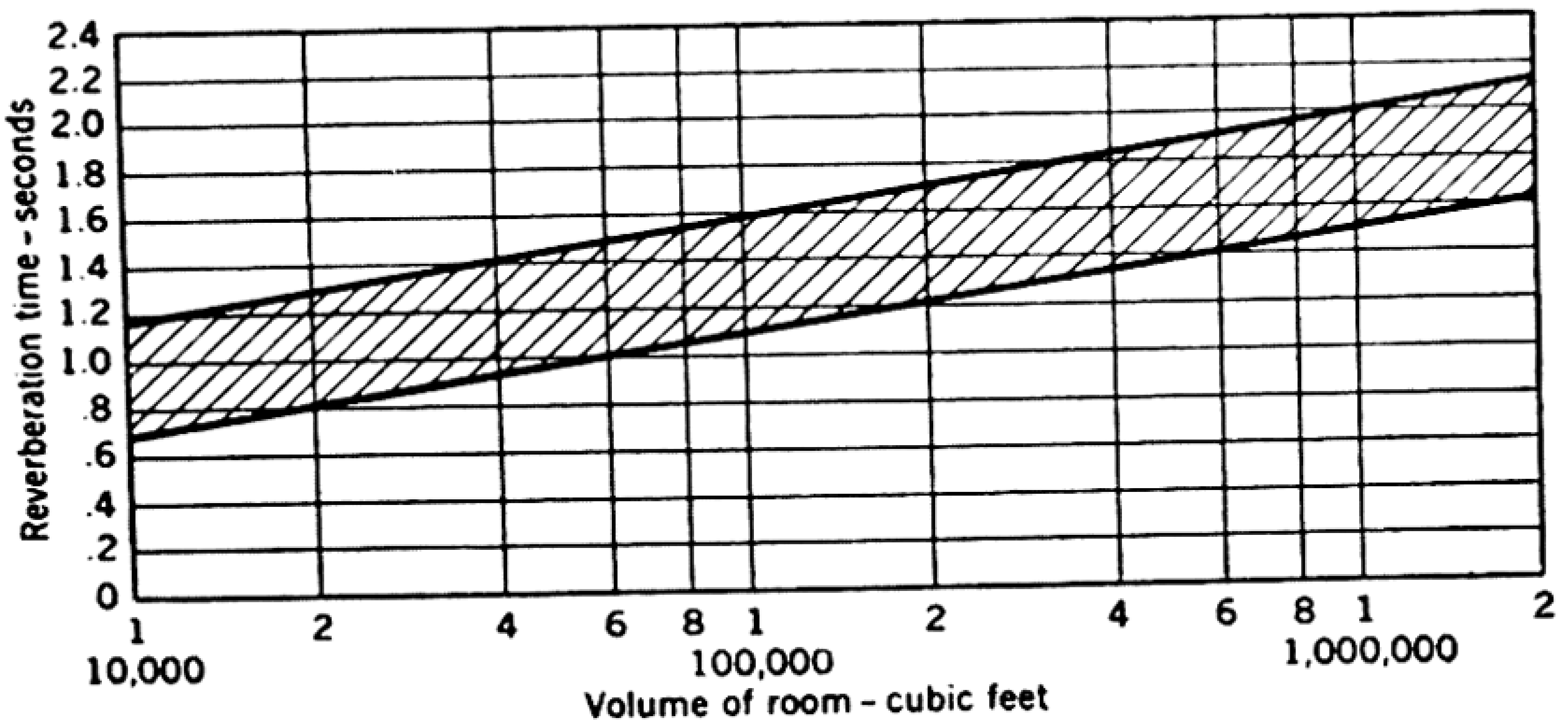

FIG. 6*b*. Optimal times of reverberation for rooms of different volume. (From *Acoustical Materials Association Bulletin VII*.)

EXAMPLE. As an example when using the data in Fig. 6*b*, consider the problem already discussed in Chapter V for the corrected room with a volume of 80,800 cubic feet. The optimal time selected for the volume was 1.3 seconds when an audience of 200 was present. From this selected time, the values of the times for other conditions of audience were calculated as:

$t = 1.8$ seconds, no audience
$t = 1.3$ " , 200 " (optimum)
$t = 0.90$ " , maximum audience

Referring to Fig. 6*b*, it is seen that the optimal value of 1.3 seconds lies in the middle of the shaded region for the volume 80,800. For no audience, the time of 1.8 seconds lies above the shaded part, indicating that the room would be too reverberant when empty. For the maximum audience, the time of 0.90 second lies below the shaded part, but this smaller time is not objectionable. The fact that the times of reverberation for this case lie outside the shaded region indicates that the audience absorption is too large a part of the total, and thus changes the acoustic conditions too much; it would be better if the effect of the audience were less.

Optimal Times of Reverberation for Various Frequencies. The times shown in Figs. 6*a* and 6*b* apply to sounds with a frequency of 512 cycles per second. If a room is adjusted to have the time specified for the frequency 512 with usual sound-absorbing materials, it is found fortunately that they also reduce sounds of higher and lower frequencies in a generally satisfactory manner. More recently, with the advent of broadcasting and sound motion pictures, it has been found necessary to consider new values for some other frequencies, particularly those of lower frequency than 512, for which most absorbing materials have small efficiences. Because of this lack of absorption, the low-frequency tones that have appeared in broadcasts sometimes " boom " out in a manner to be objectionable. New constructions have been investigated that are helpful in reducing these objectionable sounds, notably materials backed with an air space that vibrate under the action of low-frequency sounds and thus absorb energy in this region.

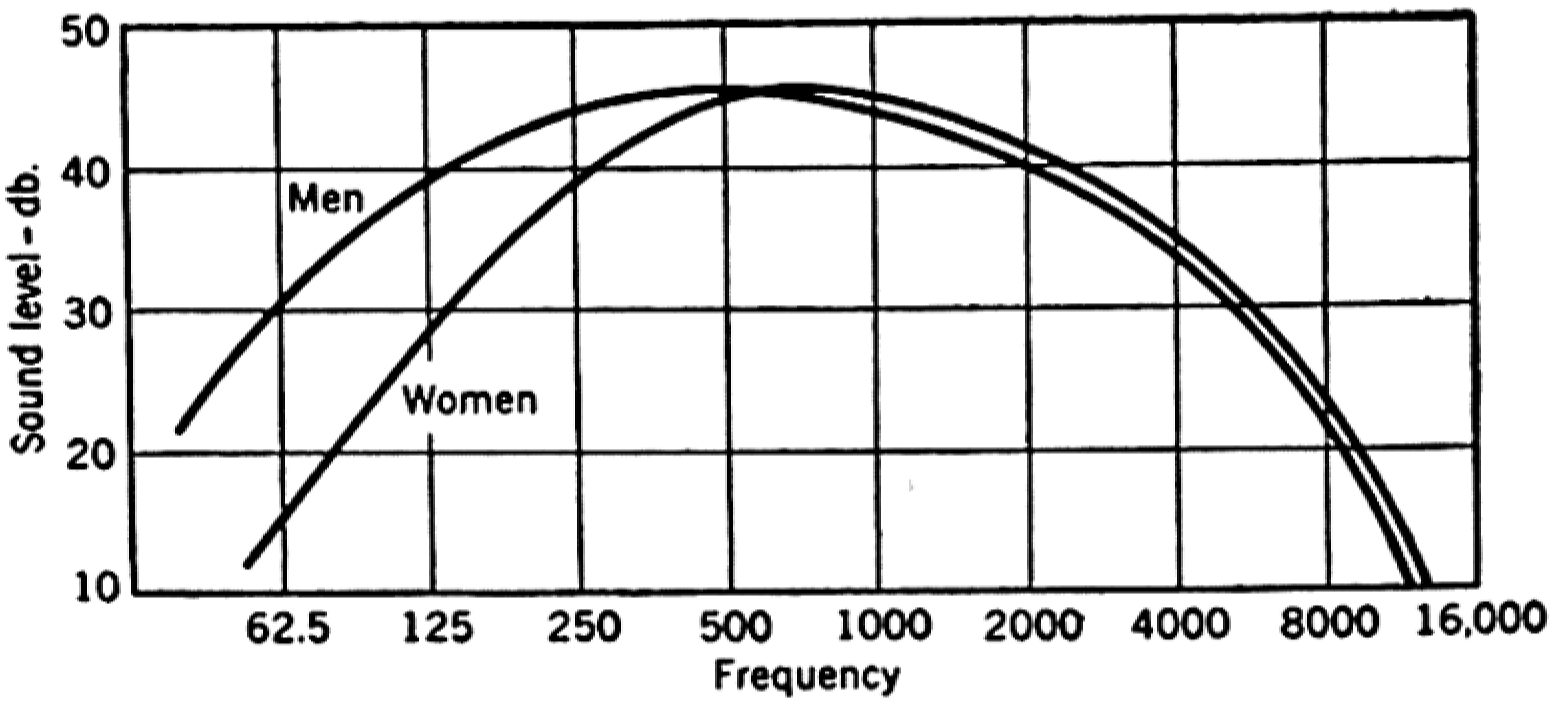

FIG. 6*c*. Average energy distribution of speech. (Fletcher.)

The problem has not been solved completely at the present time. Knudsen proposed as a general rule that it is desirable to have all the frequency components of a complex sound die away at such rates that they would all reach the threshold of hearing at the same time; otherwise, if some components persisted longer than others, the sound would be distorted.[1] To satisfy this rule, it is necessary to consider how closely absorbing materials will reduce sounds of different frequencies to bring the desired results. It is also necessary to know the average sound levels of speech and music, and the threshold level of hearing. Figure 6*c* gives data for the average speech level for men and women;[2] Fig. 6*d* gives similar data for music.[1] Fortunately the curves for men and women are approximately the same shape, with maximum values in the middle frequencies and lower values for low and high frequencies. Figure 6*e* shows the threshold of hearing. Inspection of the curves in Figs. 6*c*, 6*d*, and 6*e* indicates that sound should decrease faster for the middle-frequency sounds (i.e., the time of reverberation should be shorter) than for the low or high frequencies if all the sounds are to become inaudible at the same time. McNair developed a somewhat similar criterion, proposing that the loudness levels of all frequency components in speech or music should decay at the same constant rate.[1]

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[1] " Recent Developments in Architectural Acoustics," *Rev. Mod. Phys.*, Vol. 6, p. 1, January, 1934.

[2] H. Fletcher, " Physical Characteristics of Speech and Music," *Bell Sys. Tech. Jour.*, Vol. 10, p. 349, 1931.

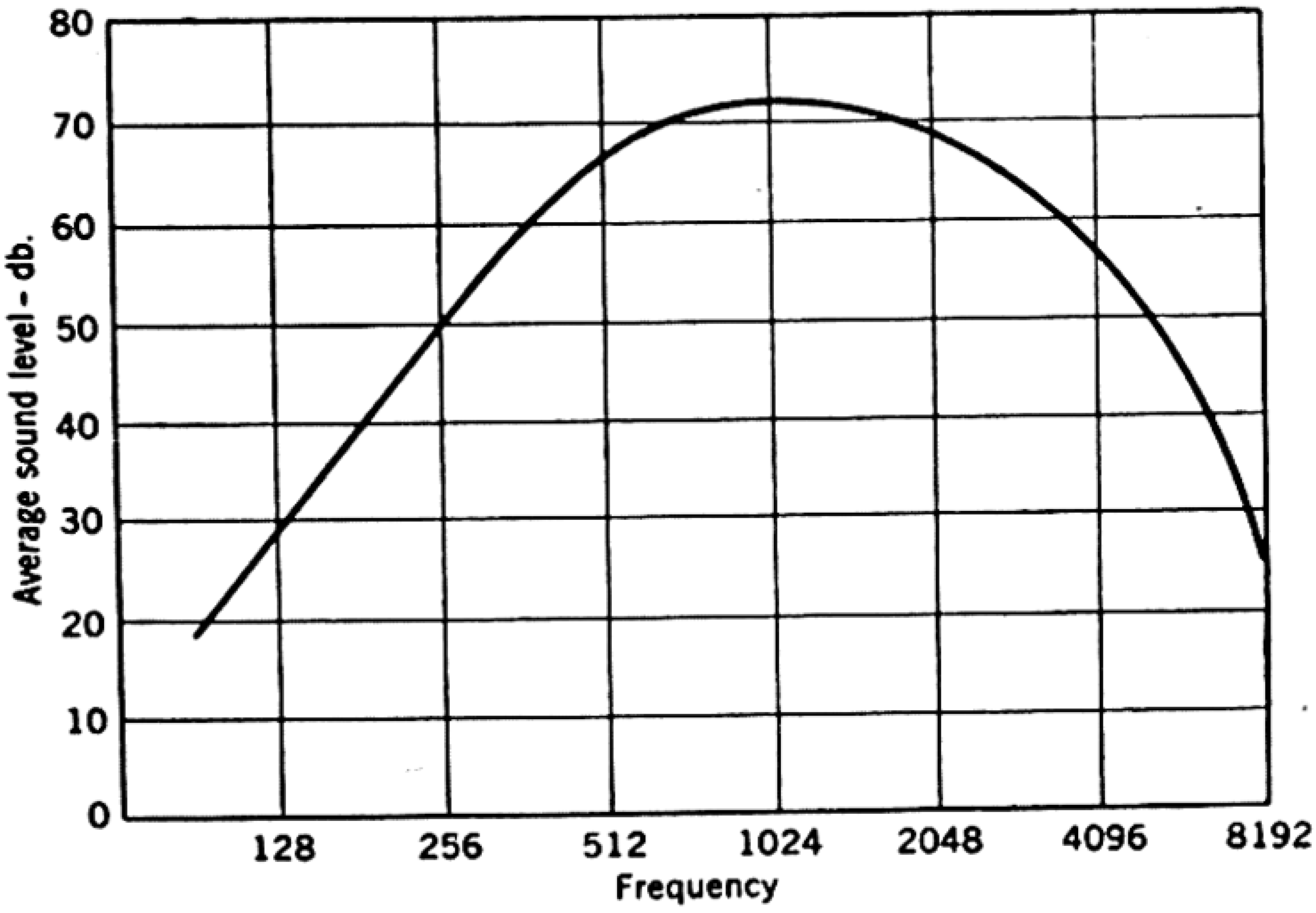

FIG. 6*d*. Average energy distribution of musical sounds. (Knudsen.)

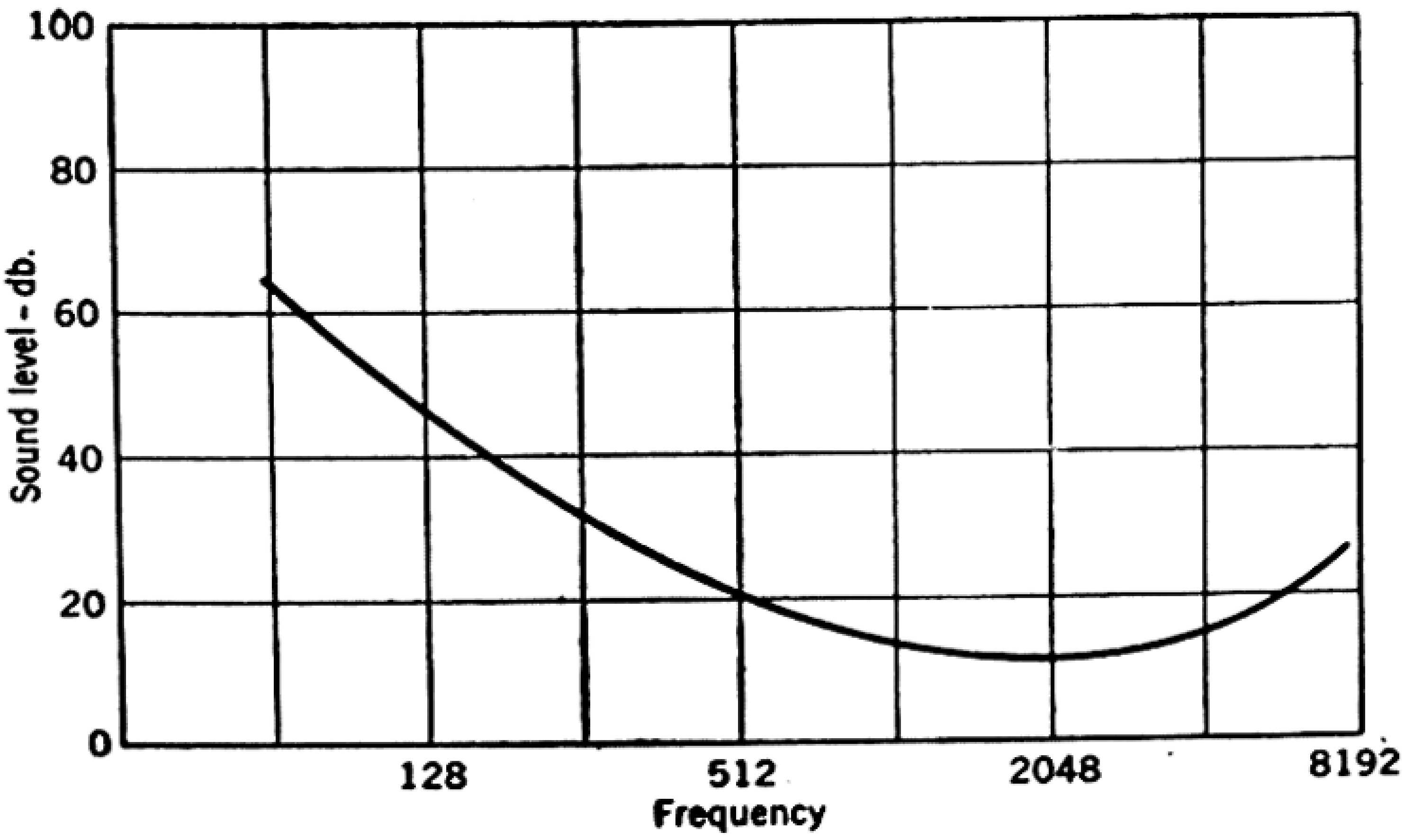

FIG. 6*e*. Threshold of hearing for different frequencies. (Steinberg.)

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[1] W. A. McNair, "Optimum Reverberation Time for Auditoriums," *Jour. Acous. Soc. Amer.*, Vol. 1, p. 242, 1930.

It appears that a combination of the theories of Knudsen and McNair would give better results than either one alone.

The adjustment of the time of reverberation is brought about in rooms by installing sound-absorbing materials. It is a fortunate circumstance that most of the common materials fit fairly closely the re-

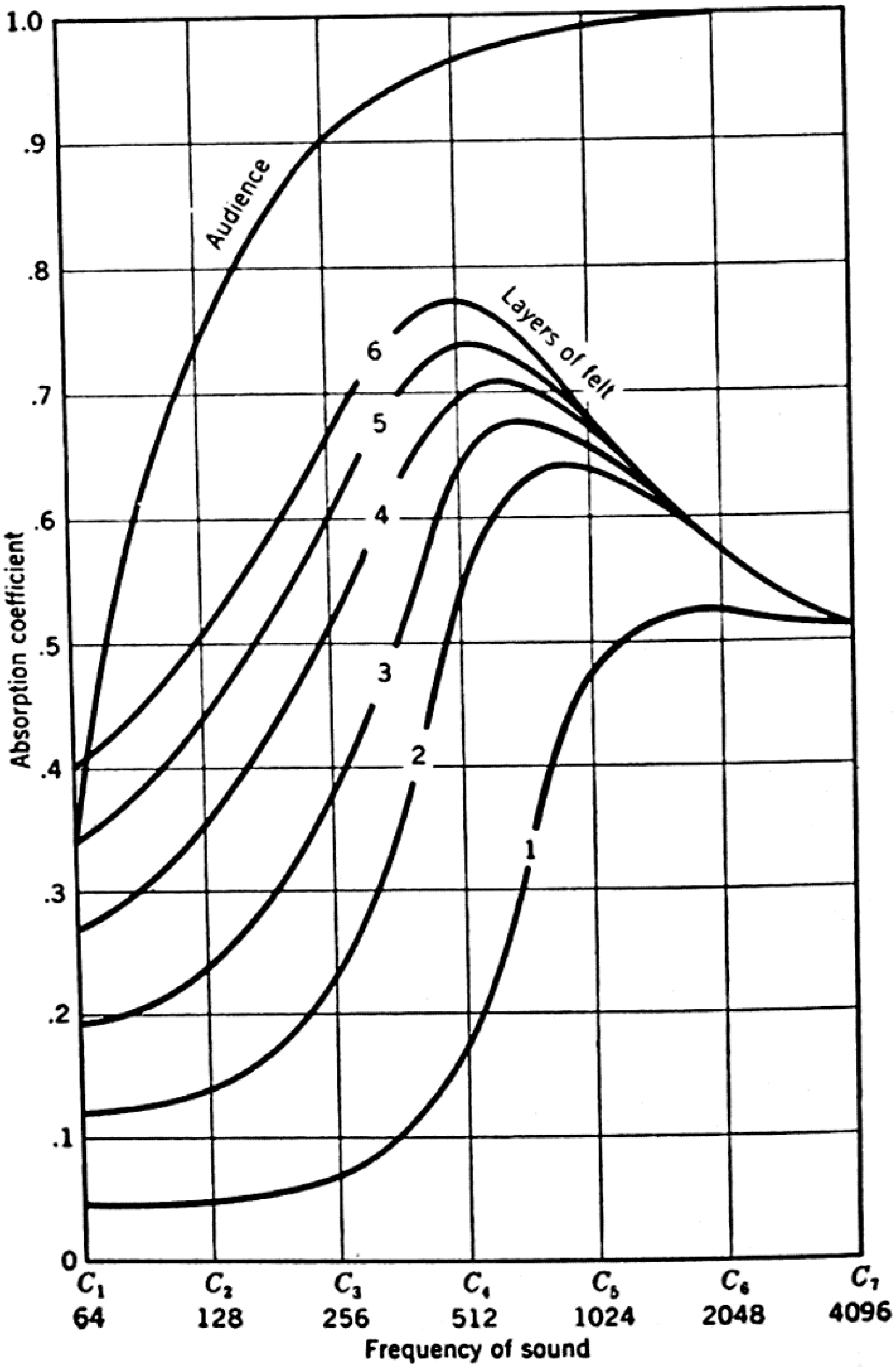

FIG. 6*f*. Absorption of hairfelt is greatest for middle frequencies of sound. (After W. C. Sabine.)

quirements for the desired reduction of sounds. Figure 6*f* shows the absorption of hairfelt, which has absorption properties generally similar to other materials, and it will be noted that the absorption efficiency is greatest for the middle frequencies and less for low and high frequencies.

More recent work, based on practical experience by Maxfield and Potwin,[1] brings suggestions for changes in the times of reverberation. Figure 6*g* shows the McNair curve, which Maxfield and Potwin re-

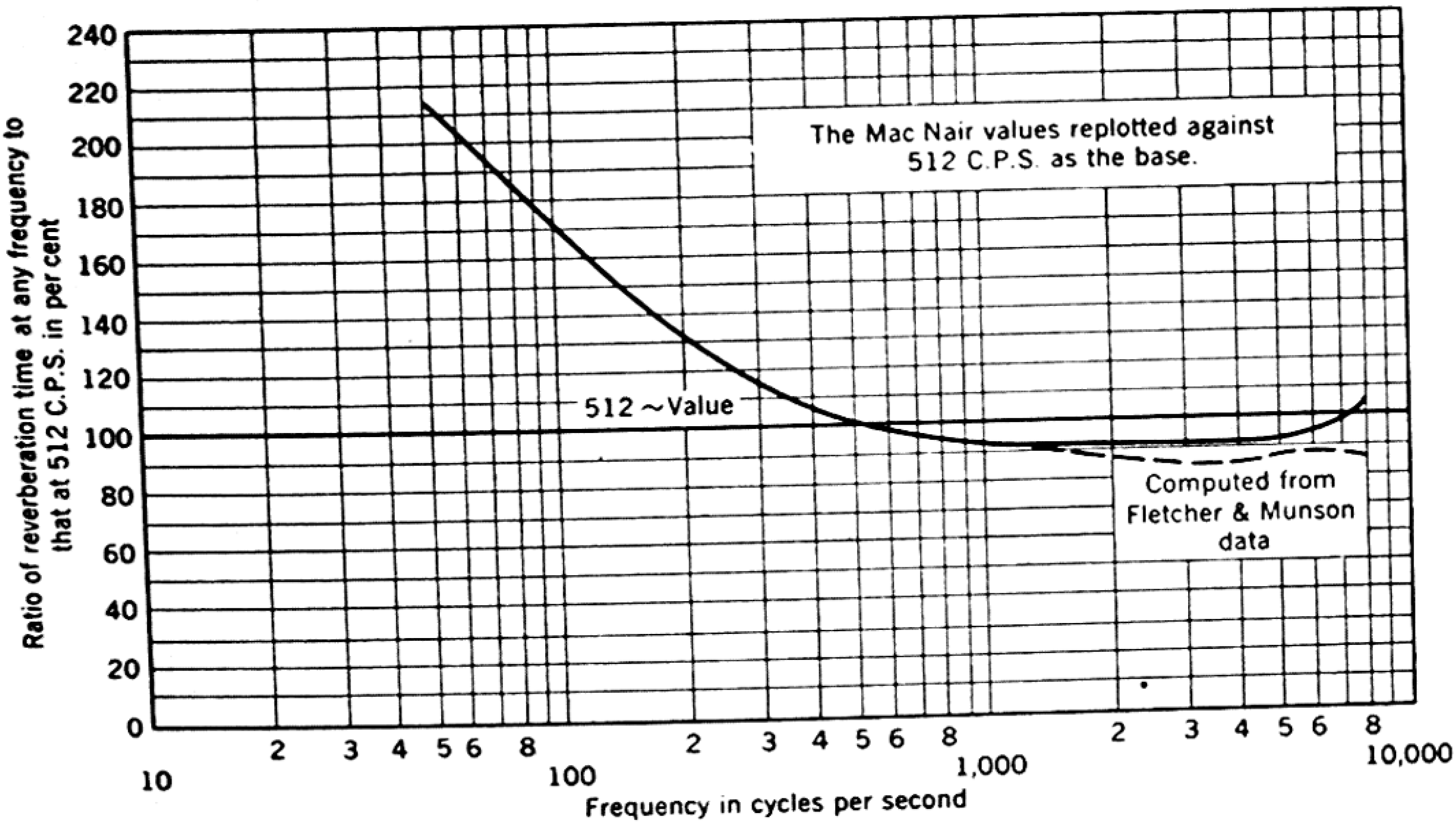

FIG. 6*g*. Times of reverberation for different frequencies, based on McNair's theory.

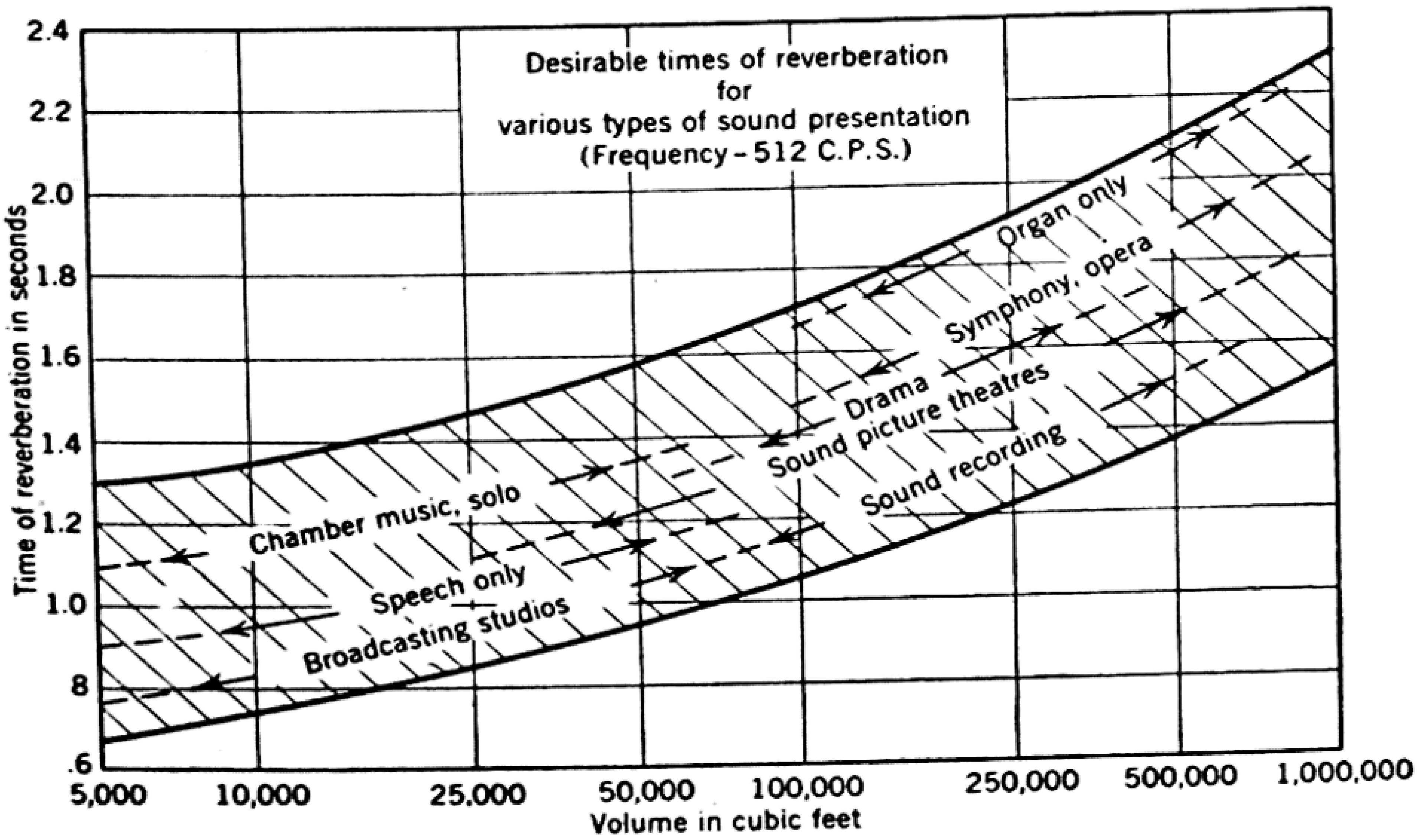

FIG. 6*h*. Desirable times of reverberation for the frequency of 512 cycles per second. (Maxfield and Potwin.)

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[1] J. P. Maxfield and C. C. Potwin, "Planning Functionally for Good Acoustics," *Jour. Acous. Soc. Amer.*, Vol. 11, p. 390, 1940.

plotted to give the times of reverberation for different frequencies compared with the times for 512 cycles as the base. They state that, for large auditoriums having volumes greater than 300,000 cubic feet, the McNair values produce exceedingly good results, particularly for music; but for rooms with volumes less than 50,000 cubic feet, a nearly flat reverberation characteristic has yielded the best general results for both speech and music. Through the courtesy of Mr. Potwin, the author has been furnished up-to-date information about the desirable times of reverberation recommended by him and Maxfield. Figure 6*h* gives the data for the frequency of 512 cycles per second; Fig 6*i* shows the corresponding times for other frequencies, referred to the frequency 512 as a base.

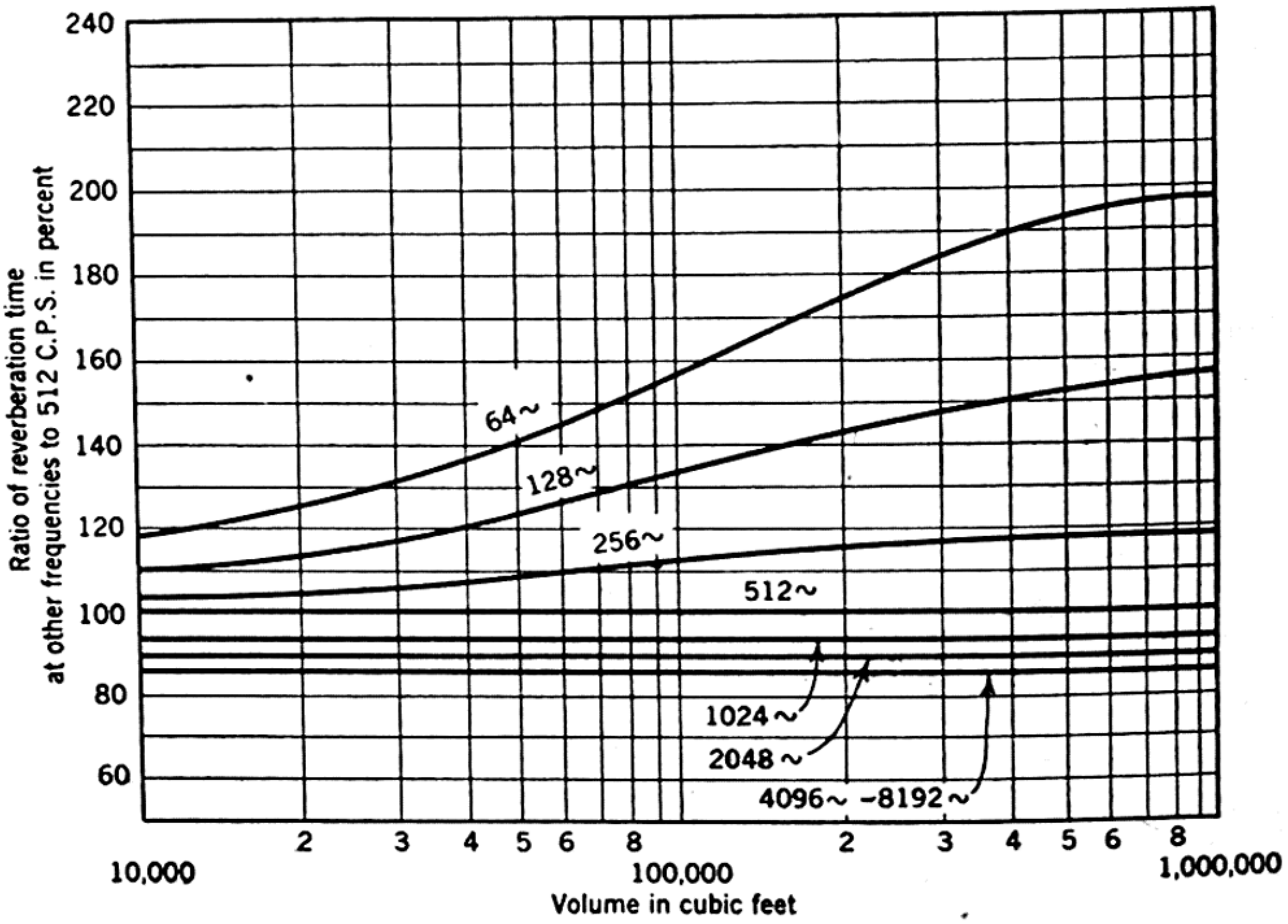

FIG. 6*i*. Times of reverberation for various frequencies referred to the desirable times for the frequency 512 shown in Fig. 6*h*. (Maxfield and Potwin.)

Times of Reverberation for Stages. All the discussion thus far has referred to reverberation in auditoriums, but very little attention has been paid to stage conditions. It is not out of the question to assume that the failure to get the expected results in some cases when using the various curves for acceptable times of reverberation may be due to neglect of stage conditions. The writer has the opinion that optimal times of reverberation may refer more logically to the stage than to the auditorium. If the stage has acceptable reverberation, the performers can obtain the best results, and the sound proceeding to the auditorium through the proscenium opening or through loud-speakers will be comparable to the acceptable acoustics of outdoor theaters. For this condition, the auditorium should be quite "dead," as explained in the writer's theory of ideal auditorium acoustics in Chapter VII. An investigation of the reverberation of stages appears to be a promising possibility in securing optimal acoustics.

CHAPTER VII

IDEAL AUDITORIUM ACOUSTICS

Introduction. Some years ago, on reading a number of published accounts of various investigations on acoustics and comparing the results, the author was led to two conclusions: first, that practically all the acoustic defects in auditoriums are due to reflected sound; and second, that speakers and musicians are aided by nearby reflecting surfaces. These conclusions are not contradictory, since the reflections from the surfaces near the source of sound come quickly after the direct sound and are beneficial (see " Blurring of Sound " in Chapter X); but the later reflected sounds cause the troubles.

These two conclusions logically and unexpectedly suggested the outdoor theater, which has practically no reflected sound and which is generally commended for its good acoustics, particularly when it is equipped with a stage that has reflecting surfaces. From this conception, to obtain ideal acoustic conditions in an indoor auditorium, it would be necessary to follow two rules:

1. Provide a stage with suitable reflecting surfaces so that performers can " hear themselves."
2. Design the auditorium for listening so that the reflected sound will be reduced to be comparable with outdoor conditions.

The remainder of this chapter is devoted to material that is intended to support this theory.

There is an incorrect assumption that reflection of sound is necessary to build up the loudness in an auditorium. It may be shown for the room described in Chapter V that the increase in sound level due to reflections that come after the first few beneficial reflections (that is for reflections occurring between 0.05 second and 1.3 seconds after the sound starts) is only about 4 db, an increase that is hardly perceptible.

For larger rooms, the increase would be somewhat greater, but it should be noted in this connection that suitable loudness in large rooms is now usually obtained by sound-amplifying systems. It thus appears that only the first few reflected sounds are beneficial, and that the later objectionable reflections do not build up the loudness as much as usually supposed.

Various publications show further that the acoustical defects in auditoriums are practically all traceable to reflected sound — echoes, excessive reverberation, interference, resonances, and imperfect articulation.[1]

Small Room Adjusted for Music. An early experiment by the author furnishes a suggestive illustration of the previous theory. In an investigation of optimal conditions for music in rooms, the fact was brought out that musicians preferred a reverberant space to play in, but that auditors found dead surroundings preferable for listening. What was done was first to adjust a room of approximately 6,500-cubic-foot volume to give optimum reverberation by placing sound-absorbing material about the walls as shown in Fig. 7*a*.

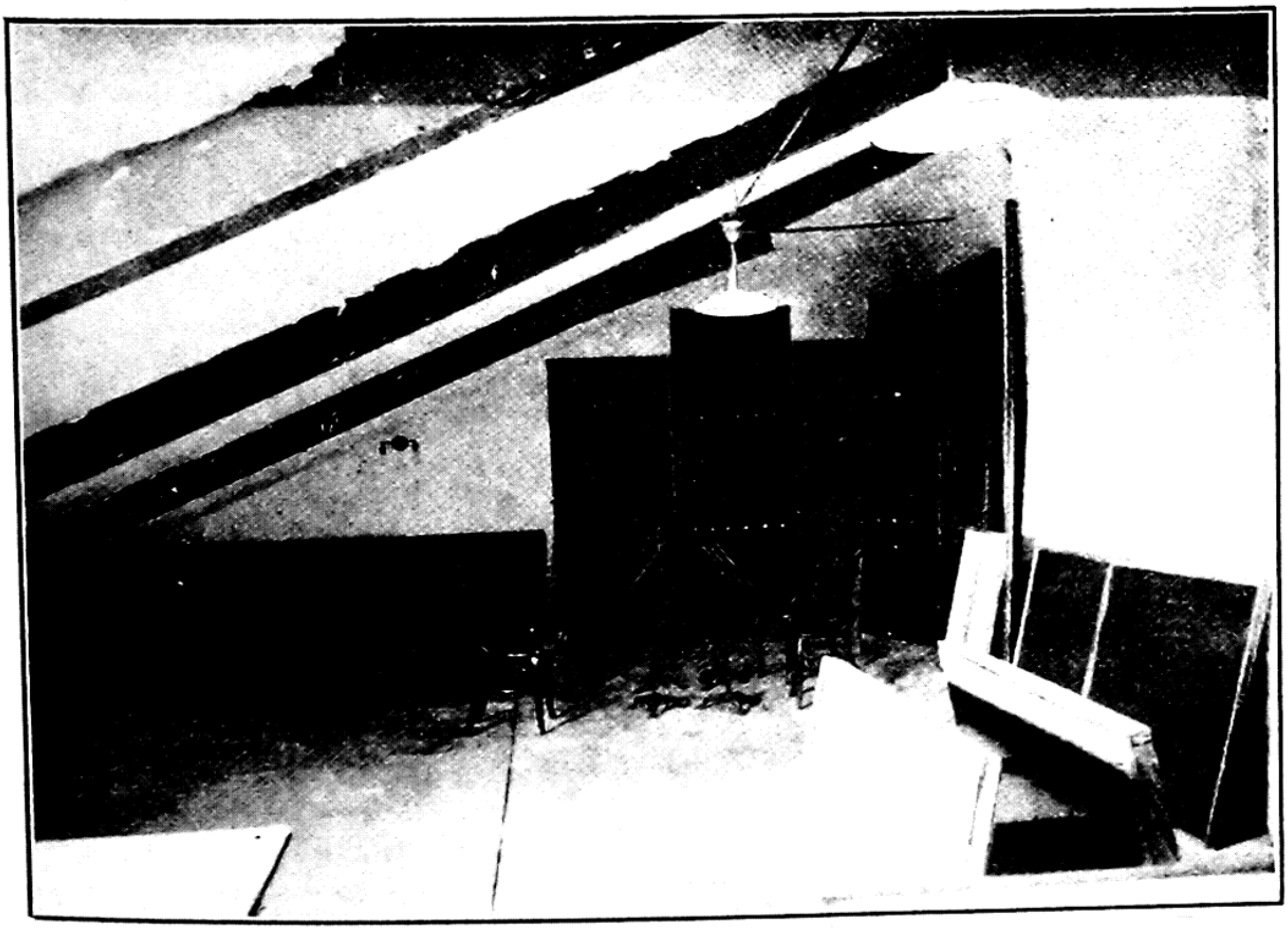

Fig. 7*a*. Experimental room adjusted with absorbing materials to give the usual optimal reverberation conditions. It was not satisfactory for musicians.

A quartette of musicians (three violins and a cello) then played at one end of the room. They did not like the musical effects, nor were the auditors pleased. But when the absorbing material was transferred from the walls about the musicians to the end of the room occupied by the listeners, the musical effects for both playing and listening improved until, in the final stage, they were thought "perfect." This arrangement gave reflecting walls that allowed the musicians to hear themselves while the other end of the room approached the deadness of outdoors. Note that the walls about the performers are non-parallel, thus reducing the troublesome normal modes and resonance.

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[1] *Science*, Vol. 67, p. 335, 1928.

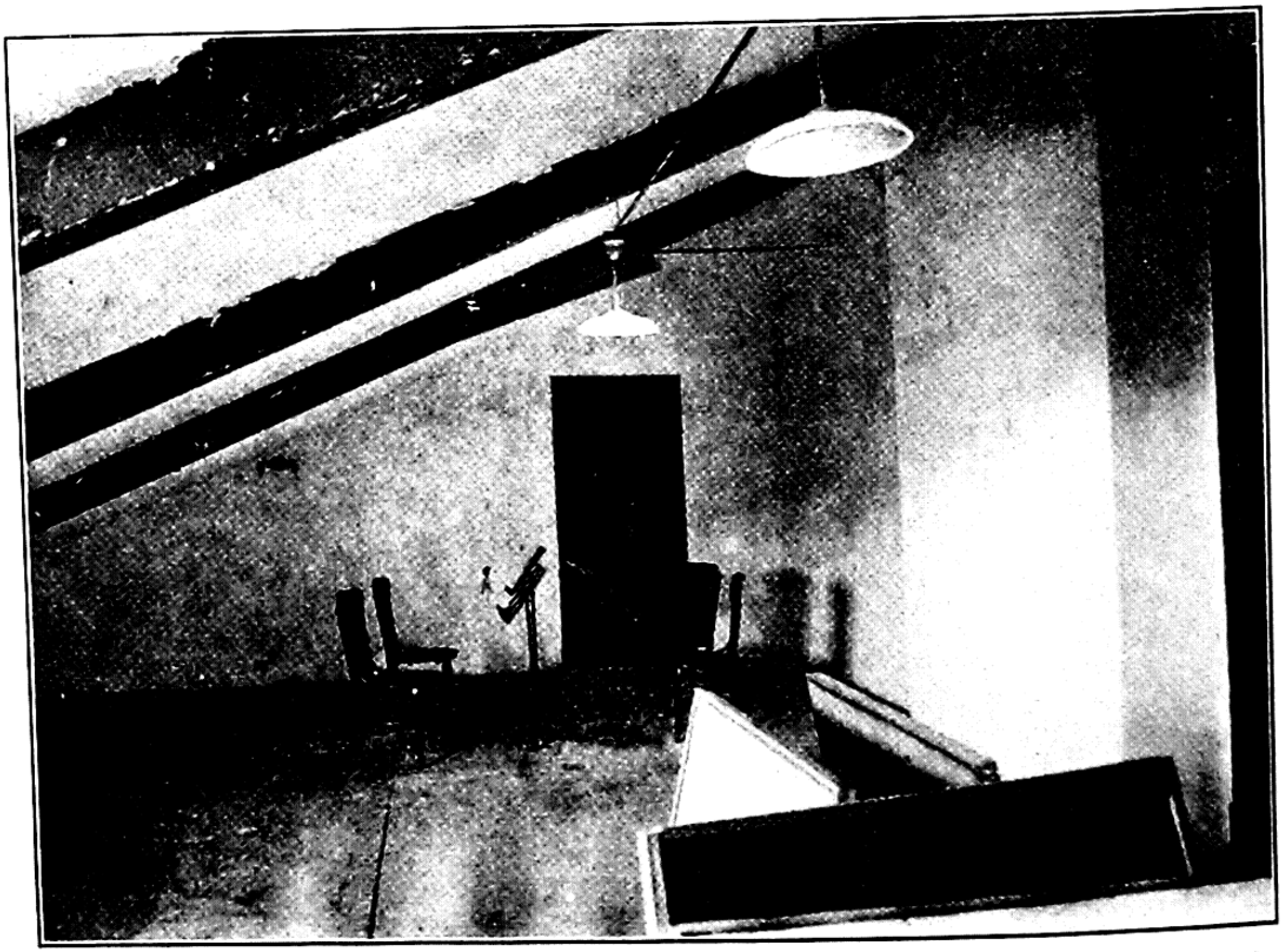

FIG. 7*b*. Absorbing material shown in Fig. 7*a* was moved to the opposite end of the room, leaving a reverberant space that musicians thought gave perfect playing conditions.

Players and Listeners in a Reverberant Room. Another experiment that gave results similar to those just described was performed in a reverberation chamber of 12,000 cubic-foot volume. In this very reverberant room, band music was played by a group of musicians who, with several observers, pronounced opinions on the acoustic effect when sound-absorbing material was gradually added to the room to reduce the time of decay of sound. Figure 7*d* shows that the musicians preferred greater reverberation (2 seconds) than the listeners (1 second), thus supporting the theory set forth.

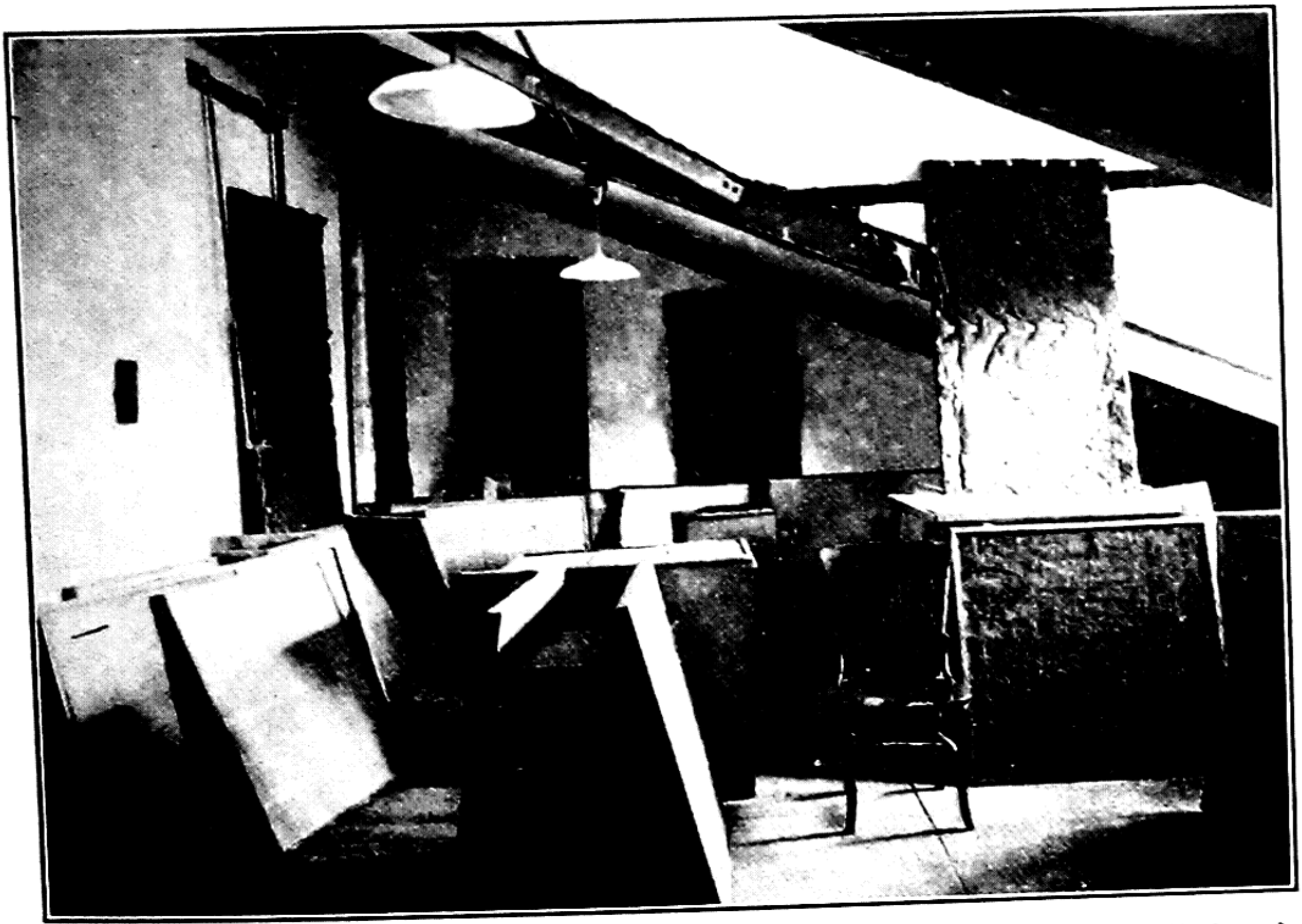

FIG. 7*c*. Photograph showing opposite end of the room in Fig. 7*a* with all the absorbing material, making this end of the room " dead " for sound. Observers thought the listening conditions were very good.

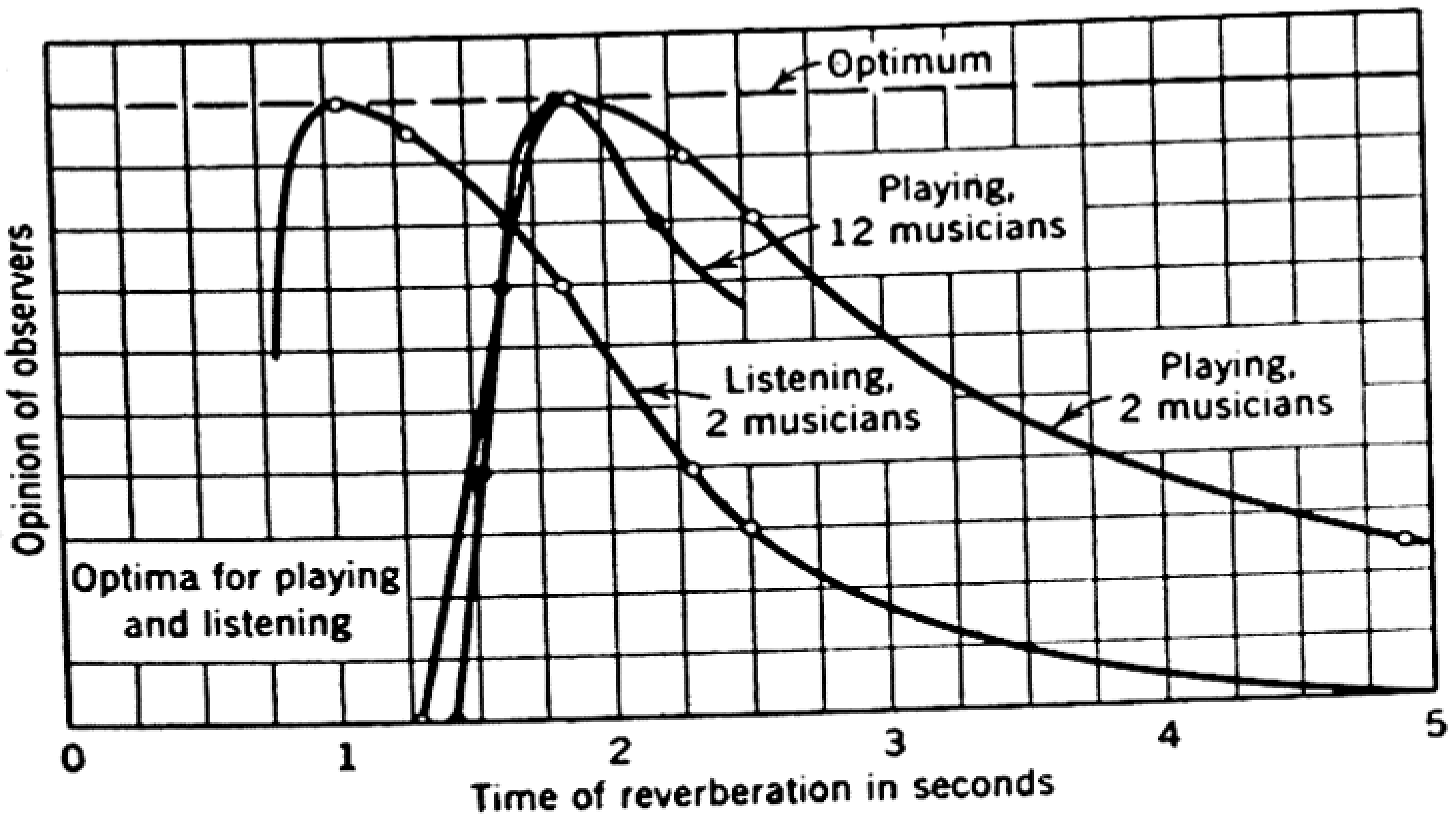

FIG. 7*d*. Results of experiments showing that musicians prefer a longer time of reverberation than listeners do.

Reflector in Large Room. A third experiment was made in the very large (1,800,000-cubic-foot volume) reverberant gymnasium at the University of Illinois, Fig. 7*e*. A reflector, 12 by 14 feet, was hung horizontally over a band stand in the center of the room, which, by means of ropes and pulleys, could be raised or lowered. When the reflector was lowered successively to positions 12, 10, 8, and 7 feet above the players, the acoustic conditions were improved. The comments of the players were: " Plays easier," " Tones more natural," " Gets better as the reflector gets lower," " Tones are smoother." Listeners at different positions on the floor found that the music became less " blurred " as the reflector was lowered, and the tempo of the music could be followed by listeners at greater distances from the central platform.

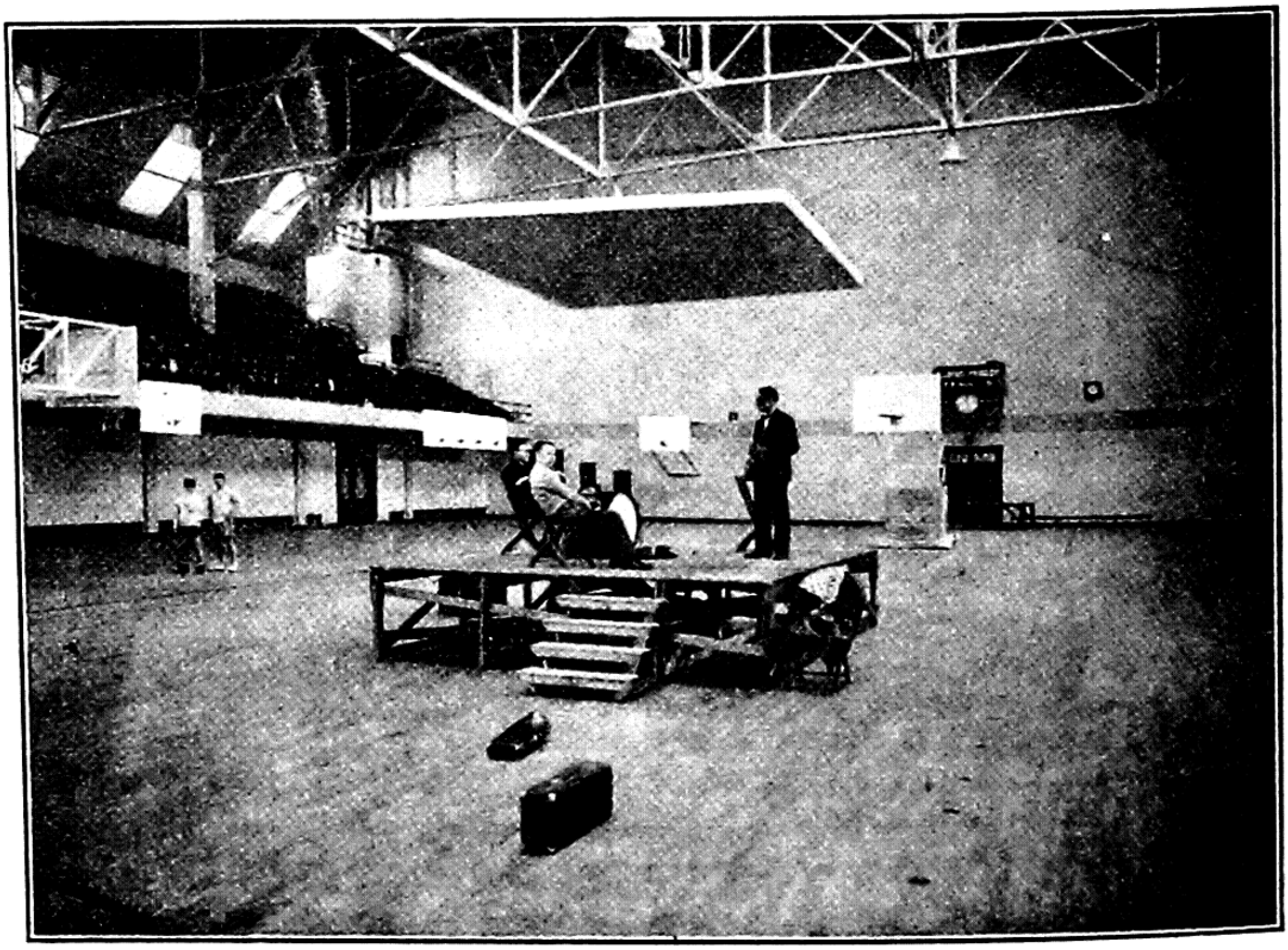

FIG. 7e. An adjustable reflector over the musicians in a reverberant room improved the conditions both for playing and for listening.

Stages Adjusted for Performers. The three experiments just described support the theory that performers like conditions by which they can hear themselves. Evidence is now set forth to show stages that have adjustments suited for obtaining good acoustic results. Figure 7*f* shows a stage designed by the author for a Music Hall in the Chicago Century of Progress. It is made up of rather shallow " boxes " without top or bottom and with slightly flaring sides, arranged so that the boxes get successively smaller toward the rear of the stage. The plane wall sections of this shell diffuse the sound more effectively than the usual curved walls of band shells and produce less annoying concentrations of musical tones for players and audience.

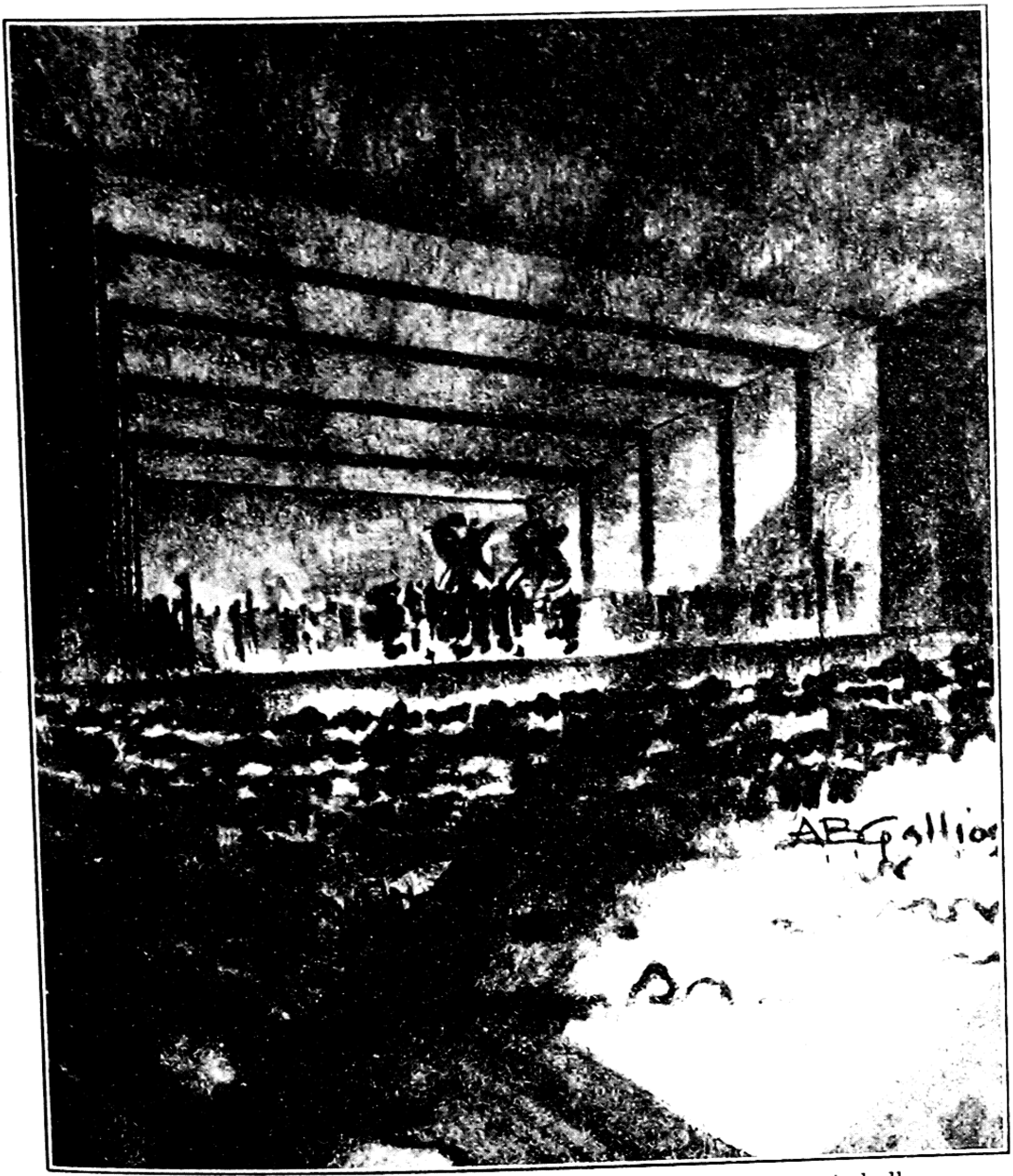

FIG. 7*f*. Perspective of a stage shell, suggested for a music hall.

Music Pavilion at the New York World's Fair. Figure 7*g* shows a stage used at the New York World's Fair that appears similar in shape to the rectangular band shell pictured in Fig. 7*f*. The listening conditions for this pavilion have the advantages of the outdoor theater. When necessary, loud-speakers can be used to amplify speaking and music. For band music, several pickup microphones are placed judiciously among the players to give a balanced reproduction through the loud-speakers.

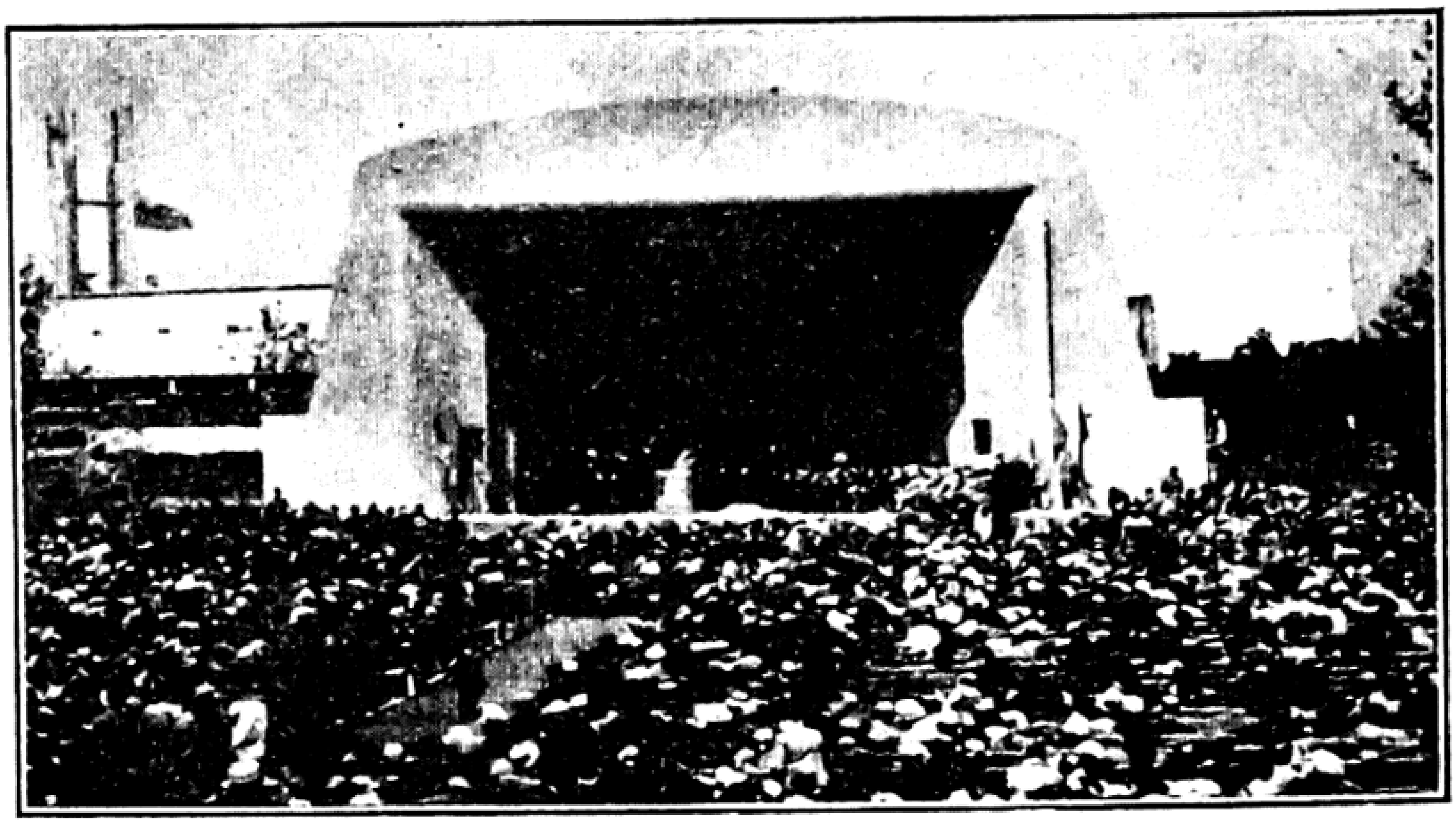

FIG. 7*g*. Music Pavilion at the New York World's Fair, with a rectangular arrangement of the walls and ceiling, giving good acoustical conditions for performers. The audience listens under acceptable outdoor acoustics.

Philadelphia Orchestra. Figure 7*h* is a photograph of the stage setting used by the Philadelphia orchestra. As already explained, the splayed walls and sloping ceiling provide the reflecting surfaces favorable to the satisfactory production of music. Dr. Leopold Stokowski, the director, likes this stage setting so much that he has it taken on tours with the orchestra to be used when the stage arrangements are not satisfactory. The auditorium used in Philadelphia has arrange-

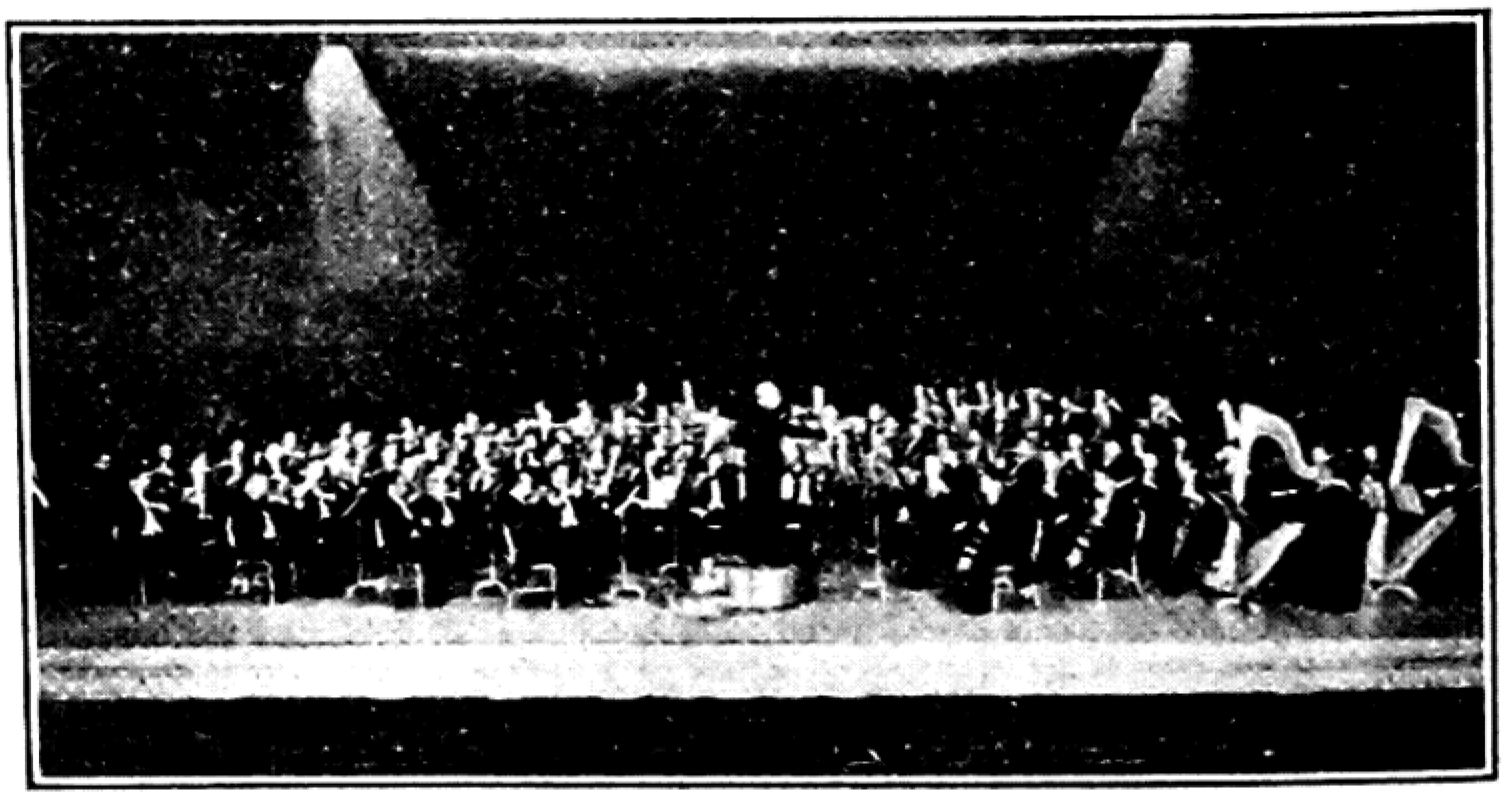

FIG. 7*h*. Portable stage used by the Philadelphia orchestra.

ments to control undue reflection and reverberation, so that it fulfills both conditions for ideal acoustics.[1]

Small Outdoor Auditorium, without Sides. Figure 7i shows an auditorium without side walls, located at Monticello, Illinois. The

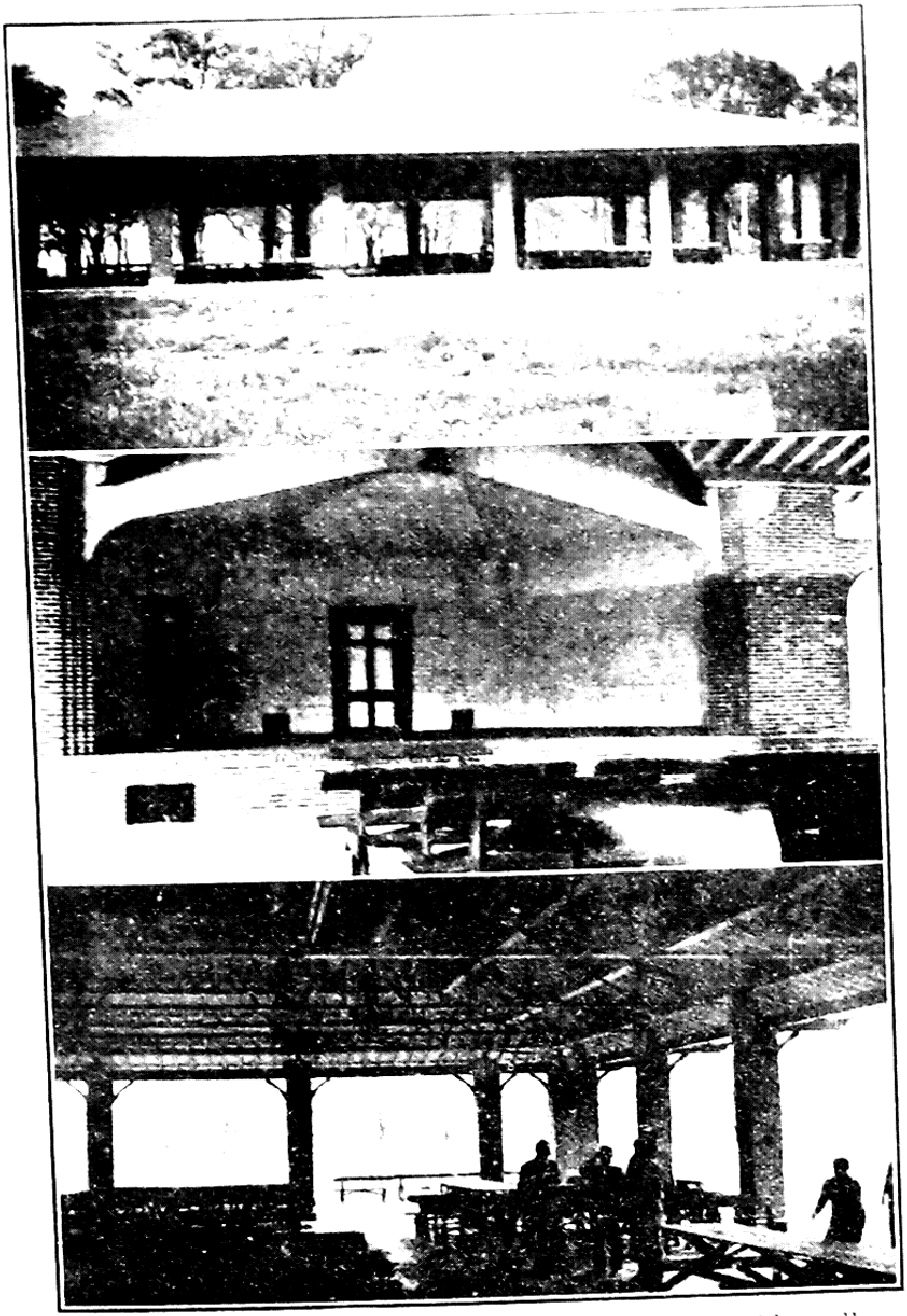

FIG. 7i. Small outdoor auditorium with a roof but with no side walls. Acoustical properties are good. (Monticello, Illinois.)

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[1] Maxfield, "Acoustic Pick-up for Philadelphia Orchestra Broadcasts," *Jour. Acous. Soc. Amer.*, Vol. 4, p. 122, 1932.

stage has the advantageous splayed walls and sloping ceiling (already discussed) and requires no particular comment. The roof over the seating space is an improvement over outdoor conditions in that the reflection from this surface beneficially reinforces the sound coming directly from the stage. Omitting the side and rear walls eliminates the objectionable reflections in auditoriums having such walls and makes the room acceptably dead in regard to reverberation. Its use is confined to the summer time, since it has no heating arrangements.

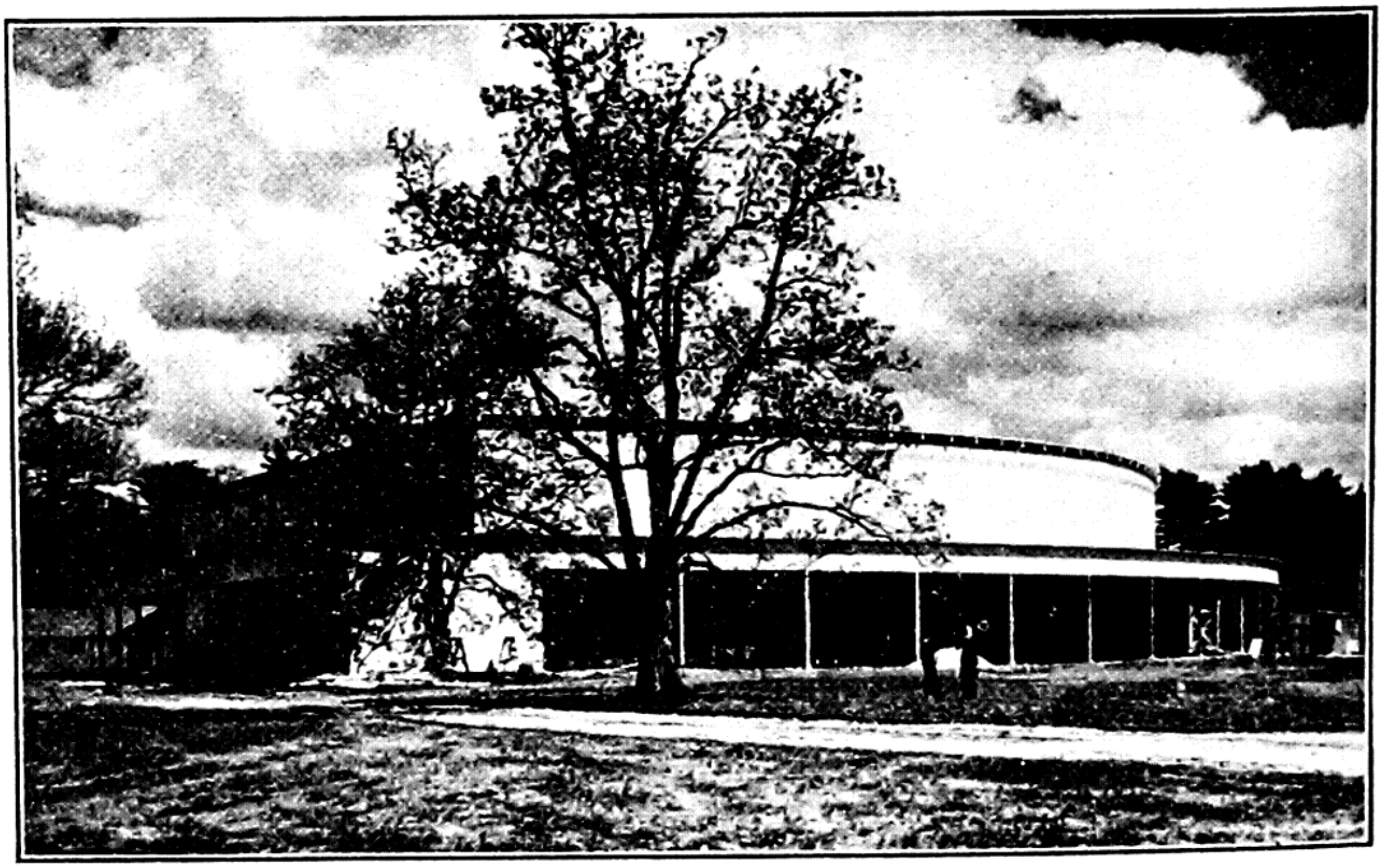
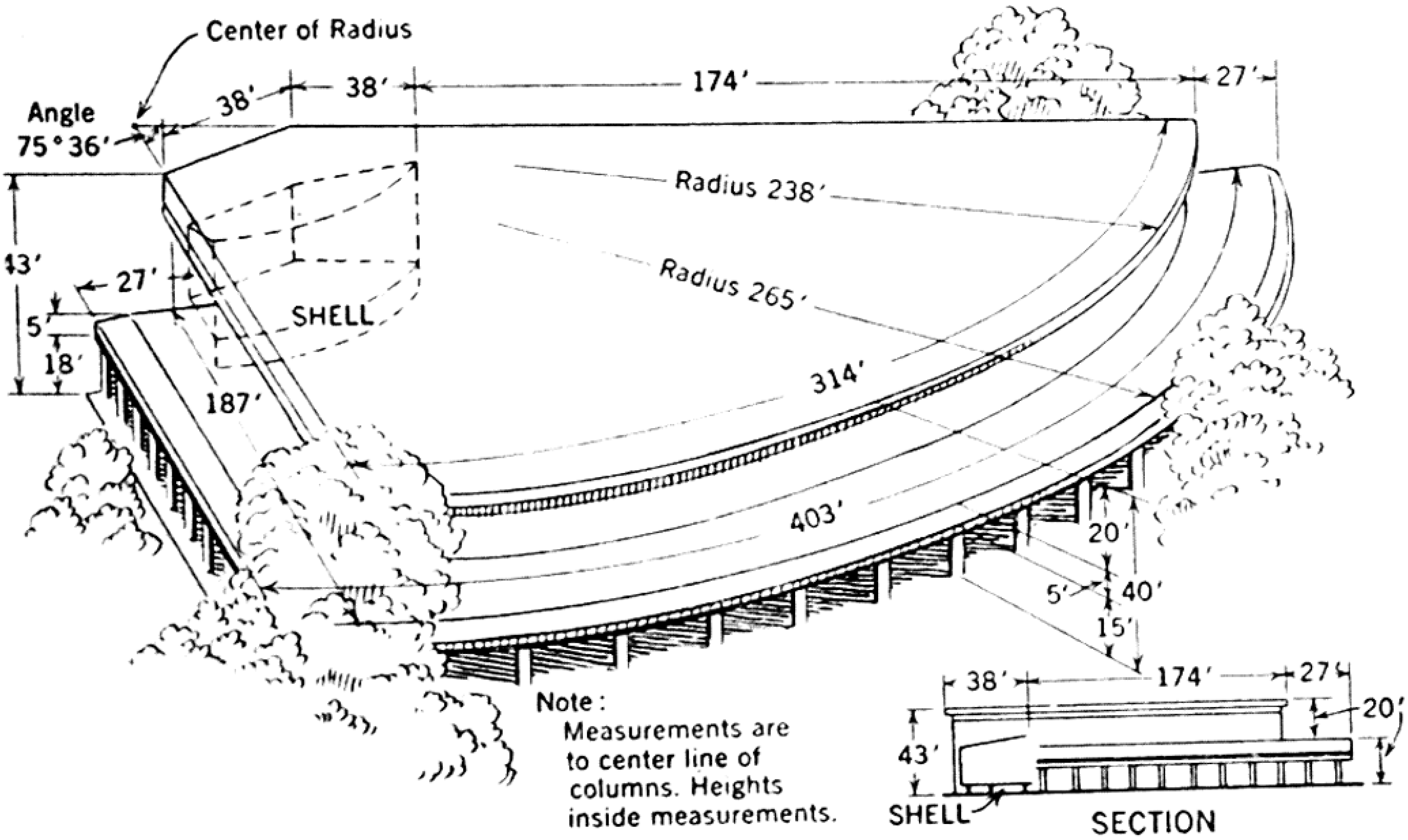


FIG. 7*j*. Berkshire Symphonic Music Shed. The rectangular stage arrangements allow satisfactory performance of music; the open sides eliminate objectionable reflections of sound. (Joseph Franz, Engineer; Ezra Stoller, Photographer.)

Berkshire Symphonic Music Shed. An auditorium, similar acoustically to the Monticello Auditorium but more pretentious, is the Berkshire Music "Shed" (really Pavilion), shown in Figs. 7*j* and 7*k*. The stage has the rectangular shape and splayed walls advantageous for the satisfactory performance of music. In addition to the advantages of open sides and reflecting roof, the Shed is equipped with a sloping reflecting board, 20 feet wide, located around the rear of the room, inclined at an angle of 30 degrees so as to reflect sound down to auditors in the rear seats. Also, extending around the outside of the open walls is a colonnade with a roof that protects auditors from the sun and rain. The acoustics are excellent for sheltered listening. The orchestra is heard clearly, not only for those seated inside and in the colonnade, but also outside for a considerable distance, to the delight of those outside who wish to sit on the grass or who bring rugs and camp chairs. The seating capacity is 6,025 inside, with the possibility of adding 3,000 more in the colonnade, and an indefinite number outside on the grass.[1] The success of this enterprise is due in large part to the interest and active participation of Mr. Joseph Franz, a member of the Music Organization, who with restricted funds worked over the original design of the architect, Eliel Saarinen, and produced the structure shown in the figures. In a letter to the author of this book, Mr. Franz wrote substantially as follows:



Note: Measurements are to center line of columns. Heights inside measurements.

FIG. 7*k*. Perspective of Berkshire Symphonic Music Shed. Acoustics satisfactory for auditors both inside and outside the shed. (Joseph Franz, Engineer.)

> I believe you have found the solution when you emphasize the stage, or as we like to call it, the shell construction. We experimented with various devices over a period of five years before building the Shed. We had our troubles in the beginning when we gave concerts outdoors and in tents. Our first shell was a curved reflector and rather high, but with this arrangement the brasses predominated over the reed and string instruments. Investigation of several existing shells gave me no comfort; they all had some inherent defect, so I experimented with various designs similar to the ones that you describe. The ceiling reflector is essential as to height and pitch to get the volume of sound into the auditorium. I found in the tents that a lower shell gave better results than a higher one. All shells cannot be built

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[1] *Architectural Forum*, Vol. 72, p. 167, 1940.

on one mode; the characteristics of the auditorium must be taken into account. Reflected sounds from distant surfaces must be avoided, but the hall must reverberate, and the materials used in the Shed take care of this feature. The acoustics of the Shed surpassed all expectations. During the concert of Peter and the Wolf, the narrator, Richard Hale, could be heard distinctly not only in every part of the Shed, but also over an area of 200 feet outside. Measurements of intensity of sound showed uniformity over the entire auditorium.

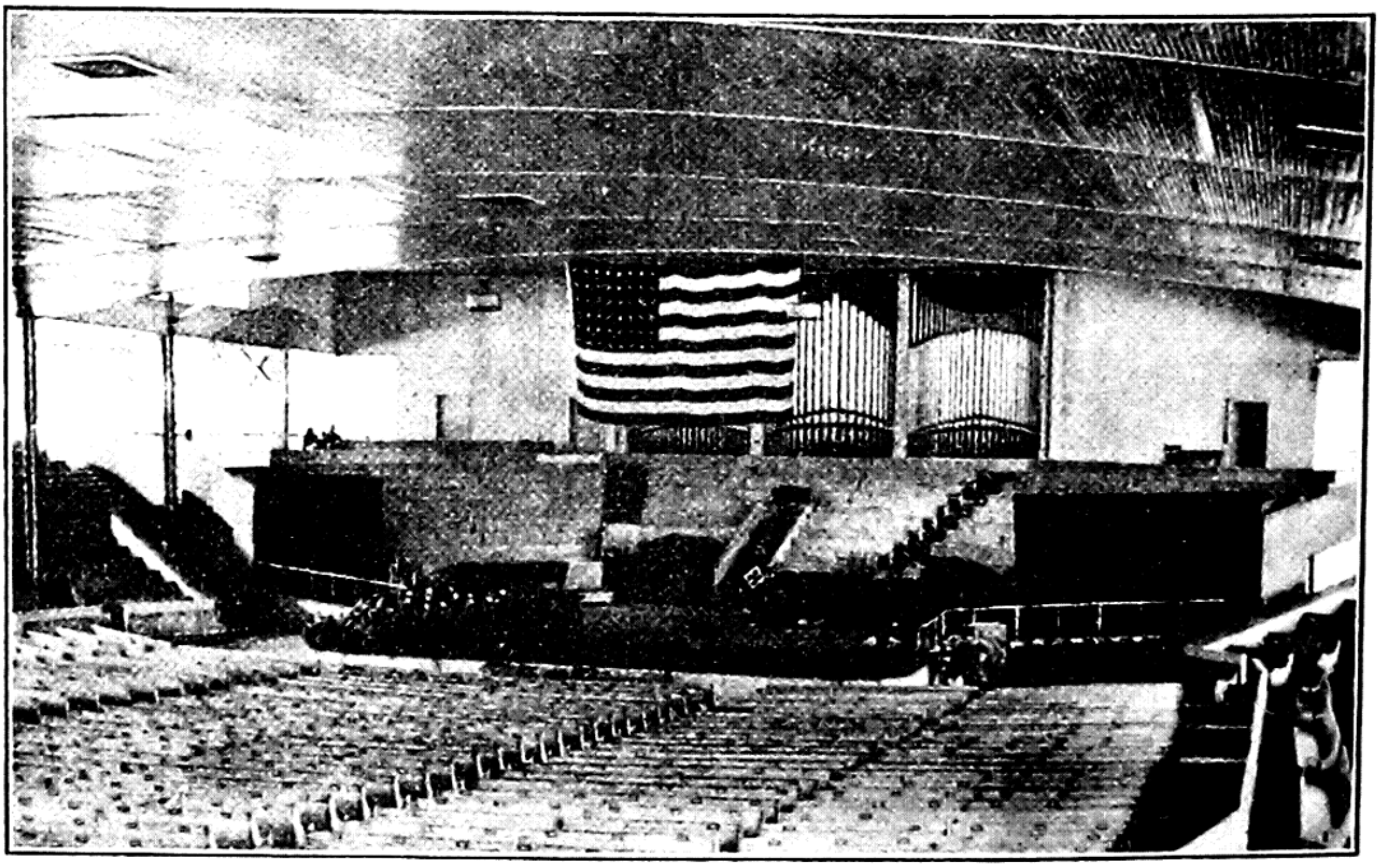

FIG. 7*l*. **Chautauqua Auditorium. Acoustics generally good, except for small audiences when the sides of the structure are closed.**

Chautauqua Auditorium. This auditorium, shown in Fig. 7*l*, is typical of a large number of similar structures which are built with open sides, a more or less flat roof, and various arrangements of the stage. Some have equipment for closing the sides in inclement weather, which would appear to be disadvantageous for good acoustics. The Chautauqua Auditorium under consideration has a slightly curved roof that concentrates sound somewhat at the rear seats, thus improving the hearing there but making the conditions less desirable in the side seats. The stage arrangements could be improved by using reflecting surfaces similar to those already described. Experiments performed in this room by Robert Watson indicate only fair articulation, or understanding of speech, but the conditions improved markedly when a loud-speaker was used. Music performance is usually good, particularly when the sides are open and a large audience is present, thus giving the desired reverberation control with elimination of the reflections.

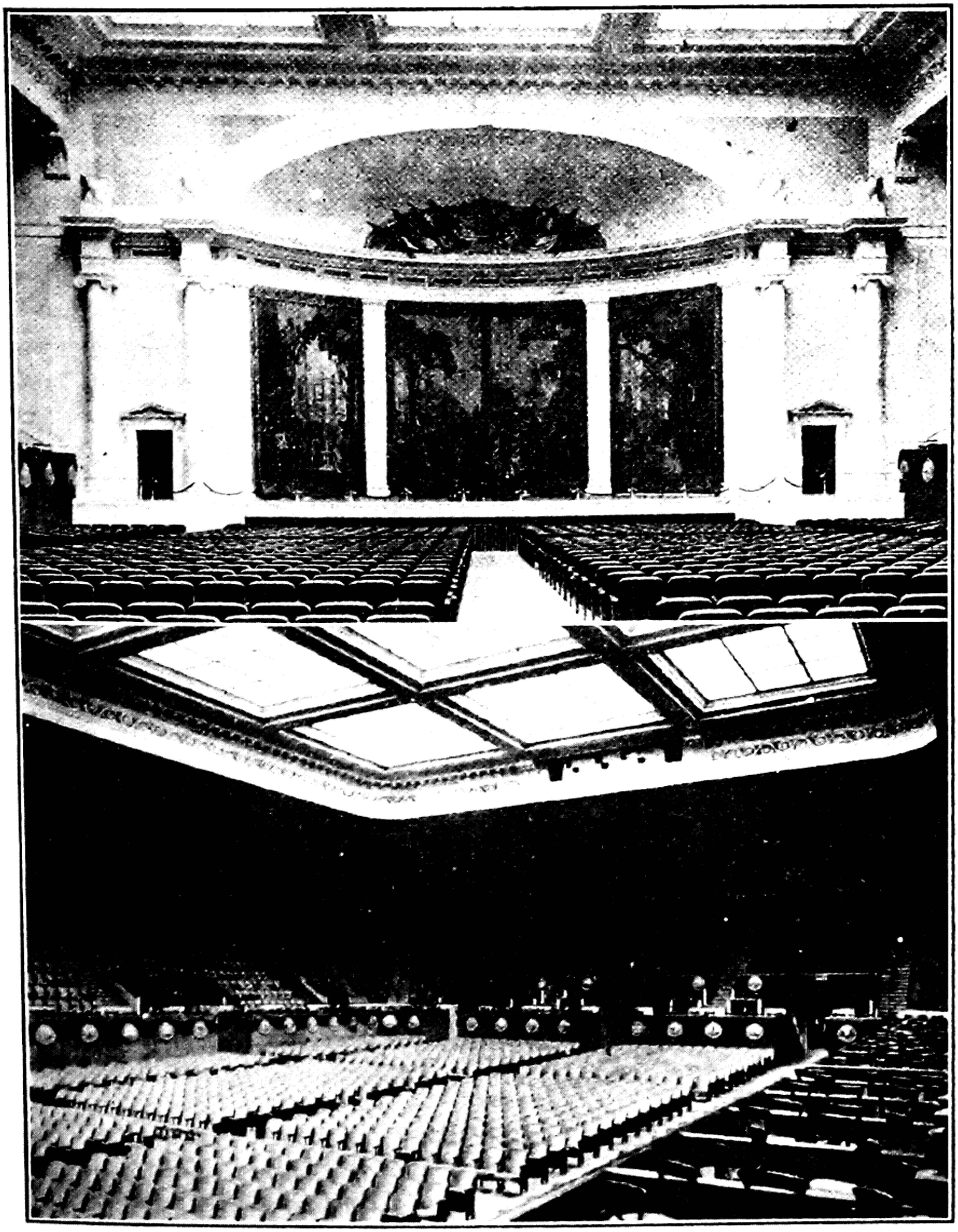

FIG. 7*m*. Constitution Hall, Washington, D. C. Side-wall reflection of sound is practically eliminated by the sloping banks of upholstered seats. (Architects: John Russel Pope and his associates, Otto R. Eggers and Daniel P. Higgins.)

Constitution Hall, Washington, D. C. The auditoriums just described have open sides and thus are limited in their use because of inclement weather and extraneous noise. The question arises as to the possibilities of introducing outdoor conditions in indoor auditoriums that are completely enclosed. One satisfactory solution is shown in Constitution Hall, Figs. 7*m* and 7*n*, in which the reflection of sound from the side walls is practically eliminated by the presence of banks of upholstered seats that extend from the central seating space obliquely back up to the walls. Sound thus passes directly to the auditors with one reflection from the ceiling, so that the conditions are rather similar to those in Berkshire Music Shed. Secondary reflections are very weak, particularly when the seats are occupied (covered) with an

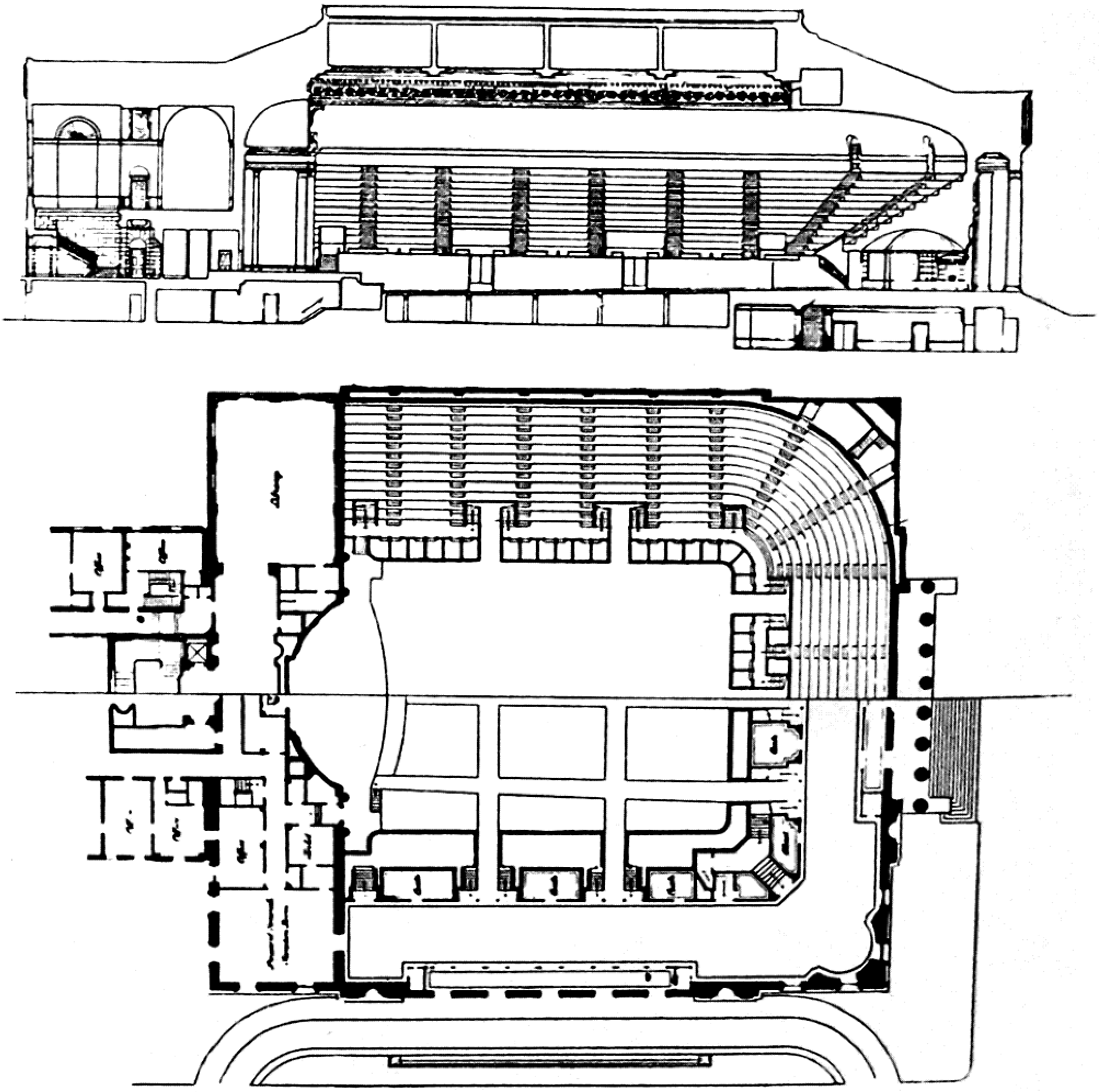

FIG. 7*n*. Plan and section of Constitution Hall.

audience. The ceiling, except for the skylight, is treated with an absorbing material. The use of a sound-amplifying system avoids the necessity of special stage arrangements.

Purdue Music Hall. This hall at Purdue University, described in the following chapter, was designed to have the desirable qualities of a reflecting stage and a dead auditorium.

Conclusion. The illustrations set forth in this chapter are intended to show the advantages stated at the beginning, namely, that performers should have stages with reflecting surfaces by which they can hear themselves and thus adjust their performance for best effect, and second, that auditors should have the listening conditions as satisfactory as outdoors, that is, with very little reverberation. The acoustic advances during the past ten years since the author set forth this theory appear to confirm the principles underlying the ideal. It is to be hoped that further experiments along the same direction will be tried, so that ultimately an " ideal " auditorium can be evolved.

Recent Experiments with Stages. Since the foregoing account was written there has appeared an account of experiments for the improvement of stage conditions for performers.[1] The reflection of sound to the performers is accomplished by a loud-speaker arrangement, by which the performer's voice is picked up by a microphone and the sound is returned to him by a loud speaker. Performers are very enthusiastic about the device, stating that it gives them the confidence that is lacking with the usual stage arrangements.

The writer is also informed by Professor H. L. Kamphoefner of the University of Oklahoma that he will soon publish a report on band shells that will give the results of his investigations during the summer of 1940 of various structures in the United States. His work was made possible by a fellowship granted by the American Institute of Architects.

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[1] Paper 5. "The Control of Acoustic Conditions on the Concert Stage," by Harold Burris-Meyer, *Jour. Acous. Soc. Amer.*, January, 1941.

CHAPTER VIII

ACOUSTIC DESIGN OF AUDITORIUMS

Advantage of Acoustic Design. If the acoustic features are prescribed in the design stage of an auditorium, the contructions and acoustic materials recommended may be installed during the process of building. This plan avoids the uncertainty and apprehension experienced by architects about the acoustic outcome and is less expensive than an acoustic correction made after the auditorium is completed. It has the further advantage that certain acoustic defects are avoided that cannot always be overcome at a later time. For example, the curved walls of the University of Illinois Auditorium could not be straightened without doing violence to the architectural appearance, and the acoustic correction was limited in its possibilities.

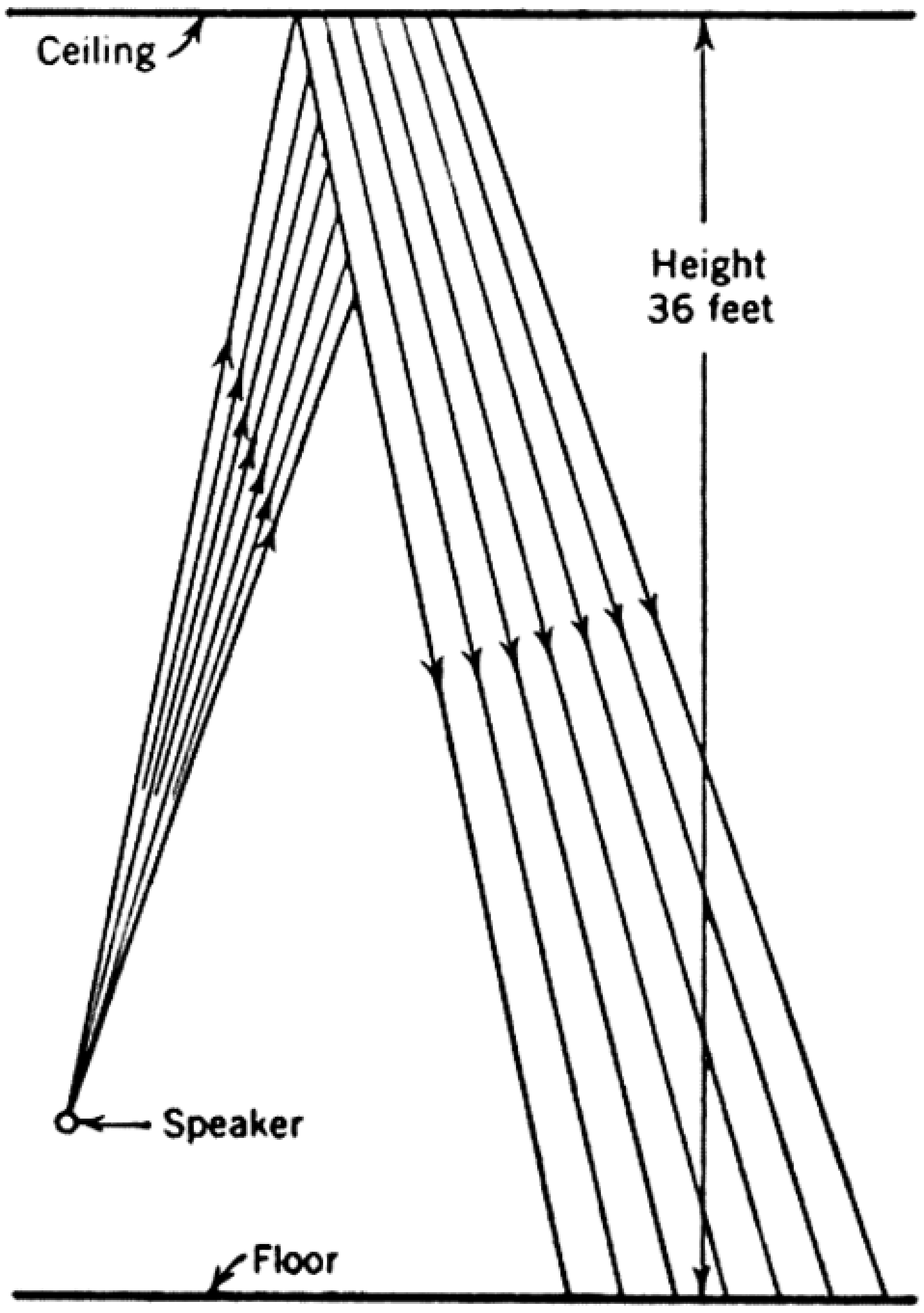

FIG. 8*a* (*a*). Reflection of sound from a plane ceiling. Height of ceiling is great enough to produce an echo by the reflected sound. A ceiling 25 feet high or less would be better.

Three Factors in Acoustic Design. The important acoustical considerations in designing an auditorium concern the *volume*, the *shape*, and the *sound absorption*.

The *volume* of the room should be decided in proportion to the intensity of the sounds that will be generated in it. For band concerts, the volume should be quite large, so that there will be sufficient space for the proper distribution of the music. Theatricals, on the other hand, which involve comparatively weak sounds, should be given in smaller rooms, if the speaking is to be loud enough, although the use of modern amplifying systems can make speaking easily understood in large auditoriums. The decision about the volume of rooms usually presents no great difficulty, since experience with rooms already built furnishes adequate guidance.

The *shape* of the room is a more important consideration and is receiving more attention because of the increasing use of sound amplifiers and the resultant possibility of echoes and other defects that are set up by reflection of sound from the various surfaces in an auditorium. As an aid in judging the effect of walls, the designer should make a geometrical study of the main sections of the room, tracing the paths of sound after reflection from the walls, noting particularly any concentrations of sound waves. A further aid in this connection is found by obtaining photographs of waves in a miniature model of the room, as illustrated in Fig. 2*c*.

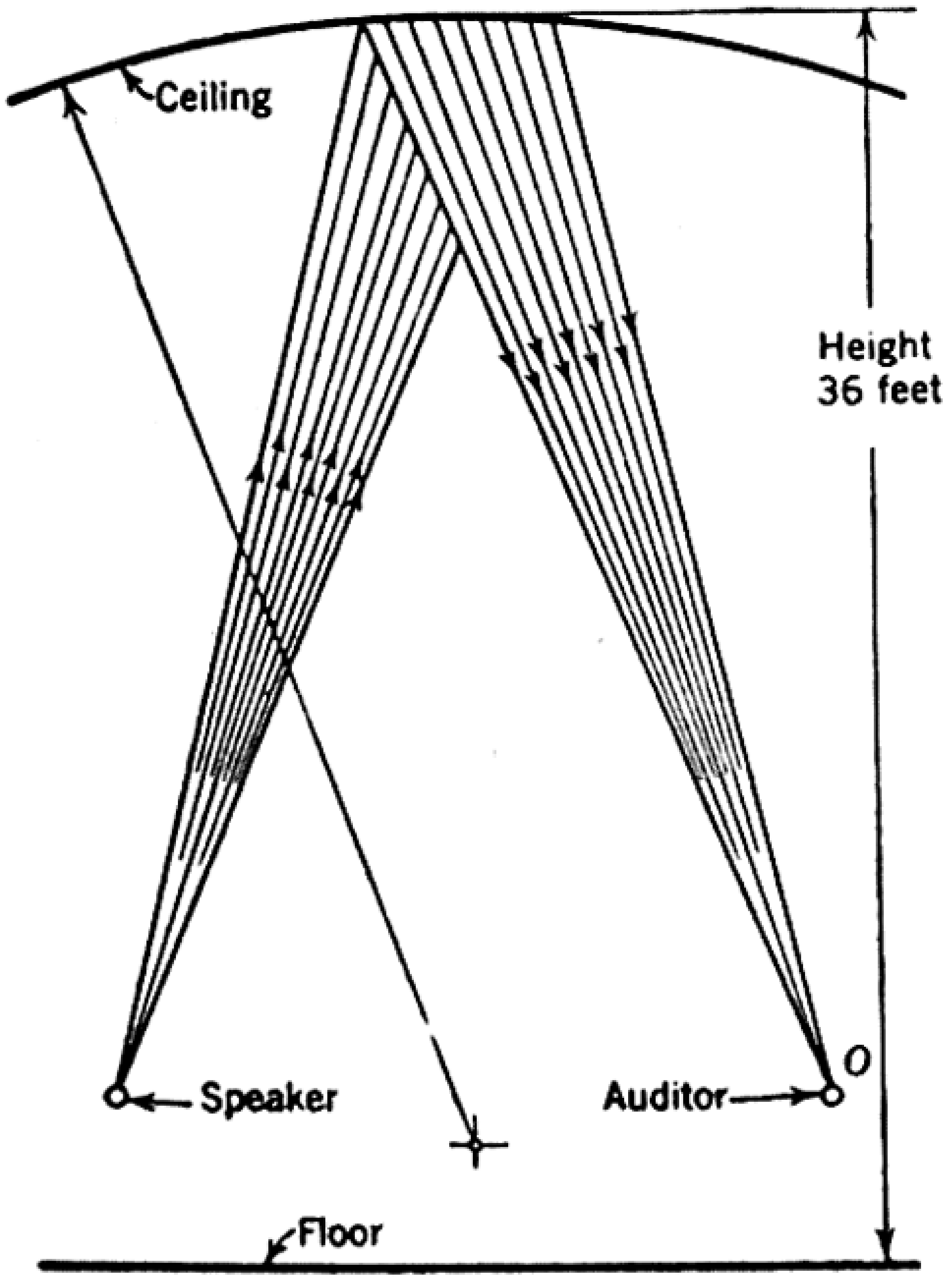

FIG. 8*a* (*b*). Sketch showing a very objectionable concentration of reflected sound by a concave ceiling. The shape of the ceiling should be plane or, better, convex.

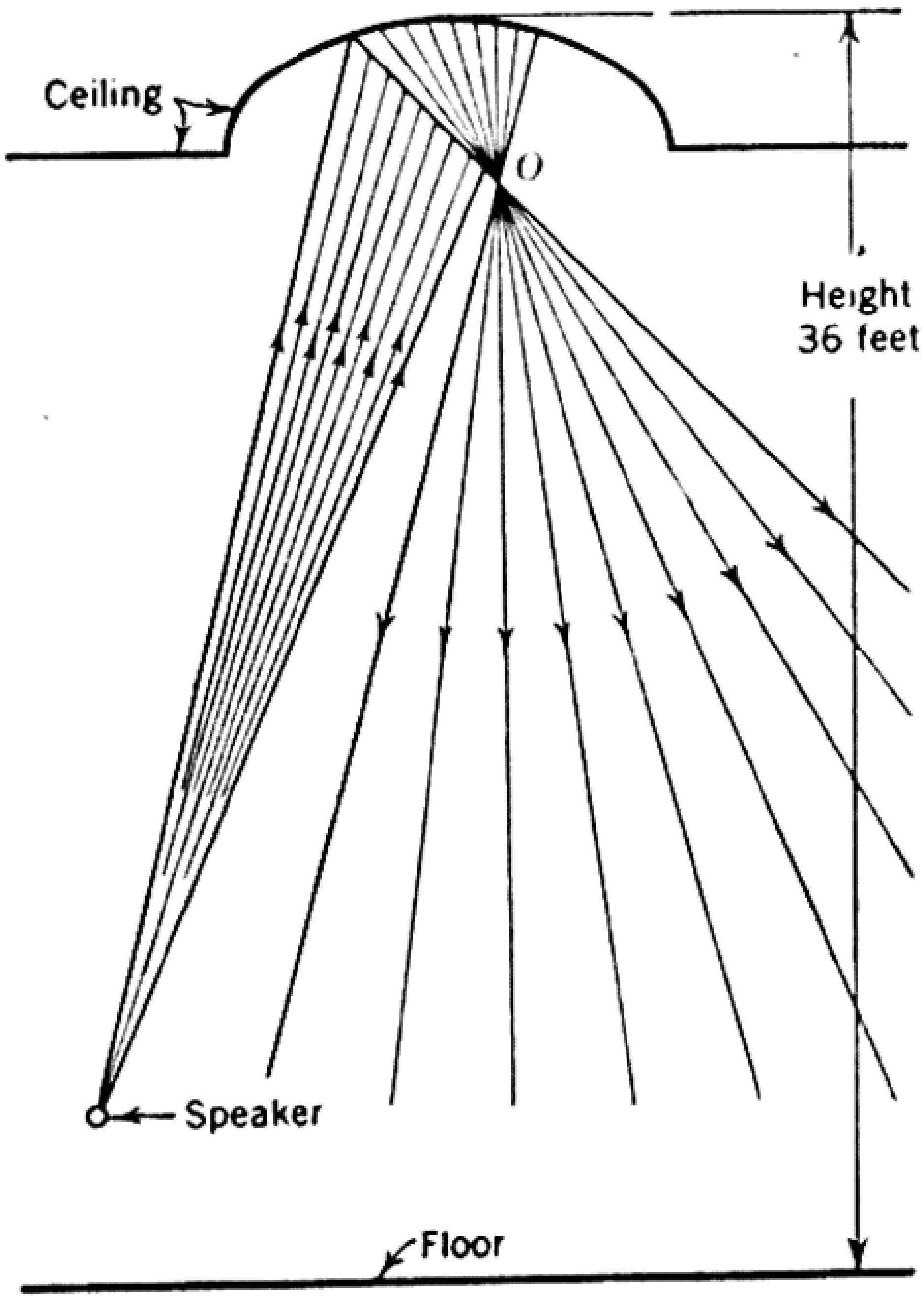

FIG. 8*a* (*c*). The concentration of sound by this domical surface is not very objectionable. The bundle of sound affected is small, the point of focus is not near the auditors, and the reflected sound spreads out rapidly in a wide bundle.

Concave walls are always a menace to good acoustics because they concentrate sound. Plane walls are better, but convex walls are still better and are being used effectively for the reduction of echo possibilities. Figure 8*a* shows the reflection of sound from three different types of ceiling. Reflection from the plane ceiling (*a*) is similar to that shown in Fig. 1*c*. For a slightly curved ceiling (*b*) the reflected sound is not much different from the plane ceiling, but converges the waves somewhat. For a small curved dome (*c*) in a ceiling, the reflected sound is brought quickly to a focus at *O*, and then spreads out rapidly in a divergent beam. A practical rule for reducing the focusing effect of a curved ceiling is the following: make the radius of curvature of the ceiling at least twice the ceiling height, or less than half the ceiling height. With the larger radius, the ceiling will be quite flat, approximating a plane surface, while for the smaller radius, the area of the curved surface will be small so that only a narrow bundle of sound will strike it and will be rapidly focused and diverged, thus producing only a small disturbance.

Figure 8*b* shows how convex walls diverge the reflected sound. The large expanse of the curved wall *ABC* tends to focus the sound at *F*, which will be disturbing for auditors in that region. By introducing convex segments *BBB* the reflected sound is diverged, thus giving a better distribution of sound in the room.

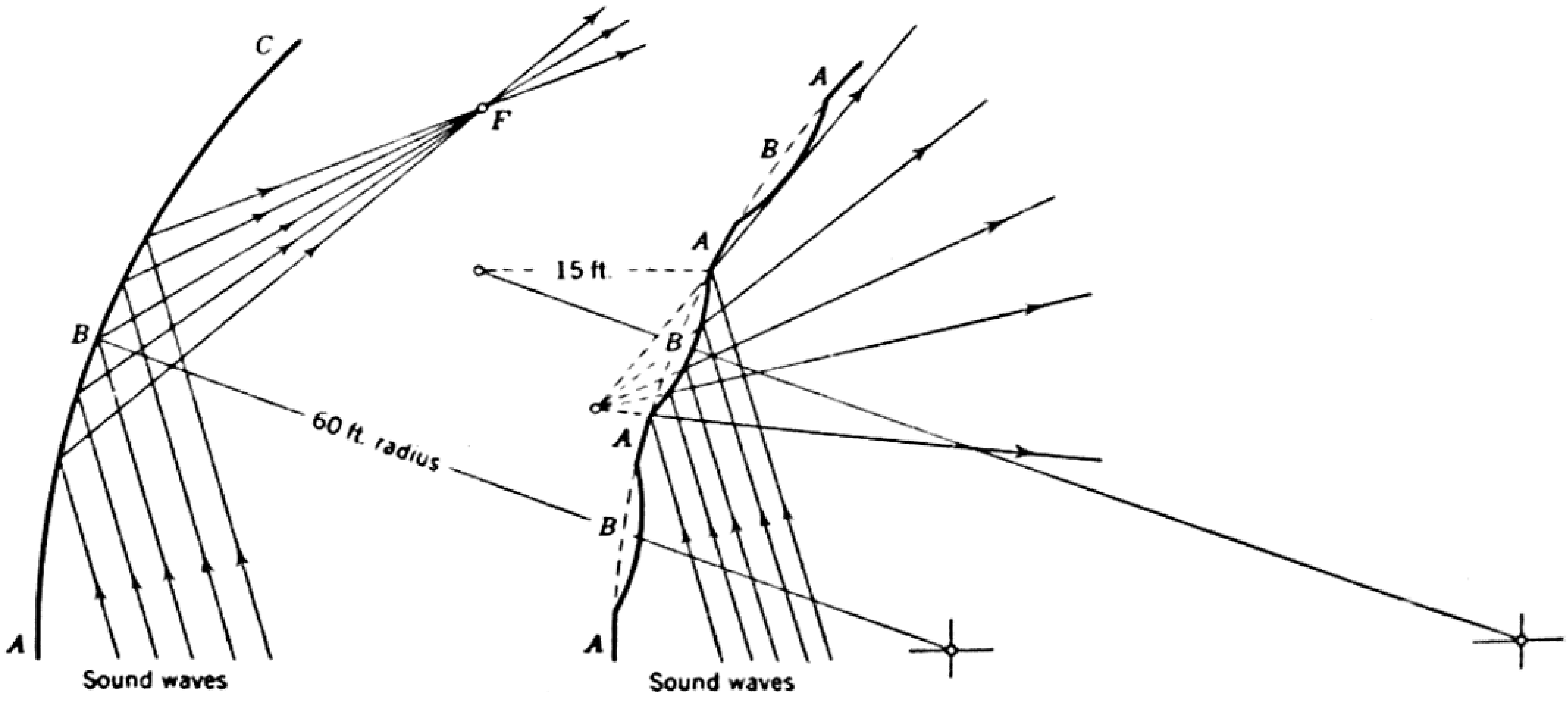

FIG. 8*b*. Convex segments in a wall break the objectionable focusing of sound that would be set up by a continuous concave wall.

Devices for Controlling Reflection from Walls. Breaking up reflected sound by convex segments as in Fig. 8*b* may be accomplished by various other devices. For example, the reflecting surface may be made in a zigzag form of plane segments which will reflect adjacent bundles of sound in different directions, thus beneficially avoiding the focusing effect. Sections of grillwork may be inserted in the wall that will allow the sound to pass through almost completely with correspondingly small reflection. If the entire wall is made up of grillwork, practically all the sound will be transmitted, an arrangement that was used in an auditorium, as shown in Fig. 9*e*. Organ and ventilation grills are useful in some cases to control reflected sound. Strips of absorbing material mounted on walls have a decided action on sound: they diffract the sound waves, as shown in Fig. 1*i*; also they absorb some energy and change the phase of the reflected sound. These various sections of convex walls, grills, and strips of absorbing material should be made in different widths so as to affect different frequency sounds. An effective and rather complicated construction to reduce echoes from a curved surface was installed on the dome ceiling of the University of Illinois Auditorium. See Fig. 9*h*.

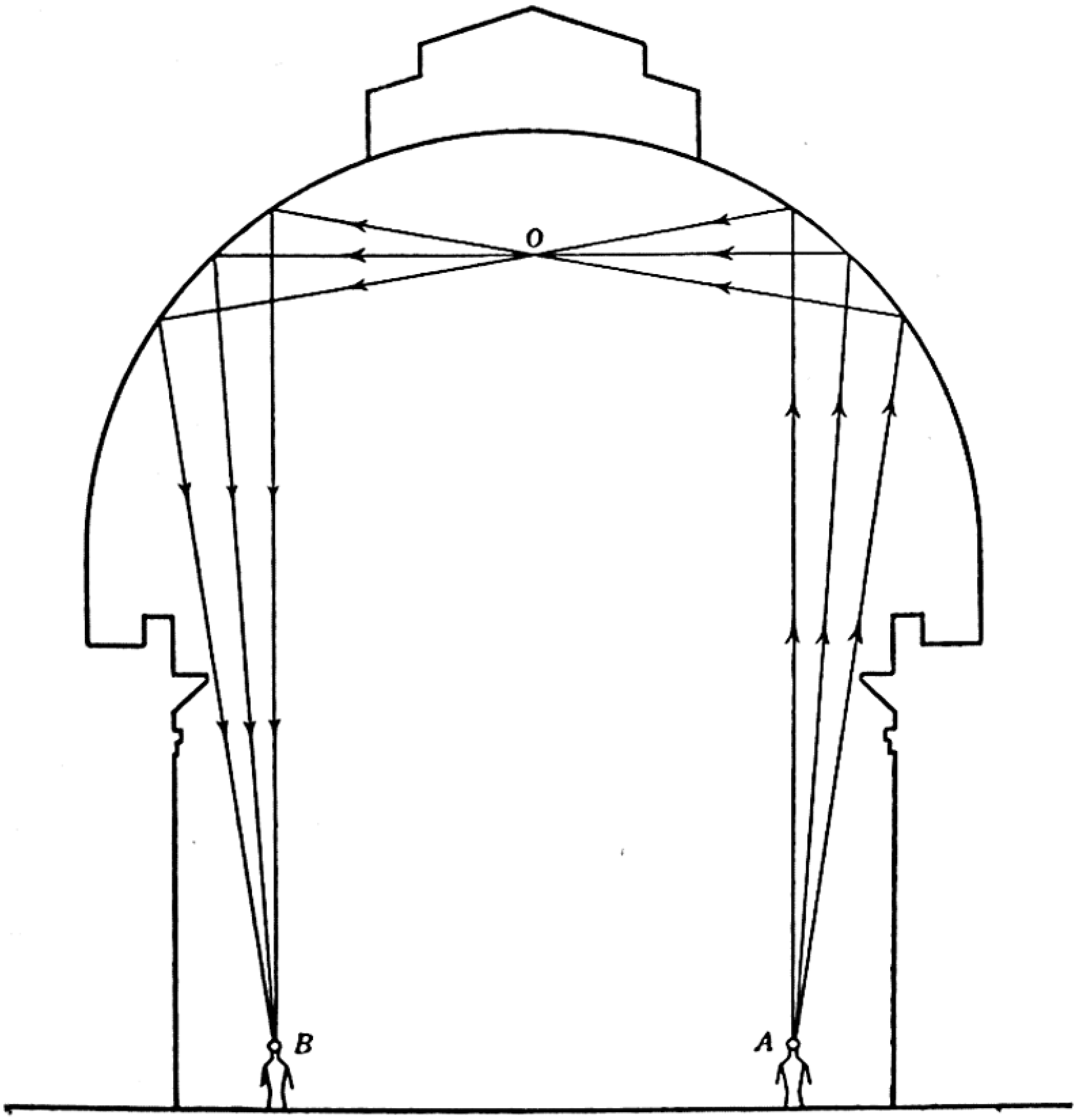

FIG. 8*c*. Sketch showing how an echo is formed by two reflections from a dome surface.

Figure 8*c* shows how an echo will be formed after two reflections of sound. The auditor *B* first gets the sound directly from the speaker *A* and then an echo some time later after the reflections come from the dome surface. This effect can be reduced somewhat by coffering the dome surface, or by introducing grills or very effective sound-absorbing constructions in panel form, but there is a strong possibility that some echo will remain.

An advantageous arrangement for reducing sound by two reflections is shown in Fig. 8*d* for a Gothic ceiling. Any sound passing to the ceiling strikes the absorbing material on one slant wall and is then reflected to the opposite wall for further absorption before it returns to the floor. It thus acts as a double absorption.

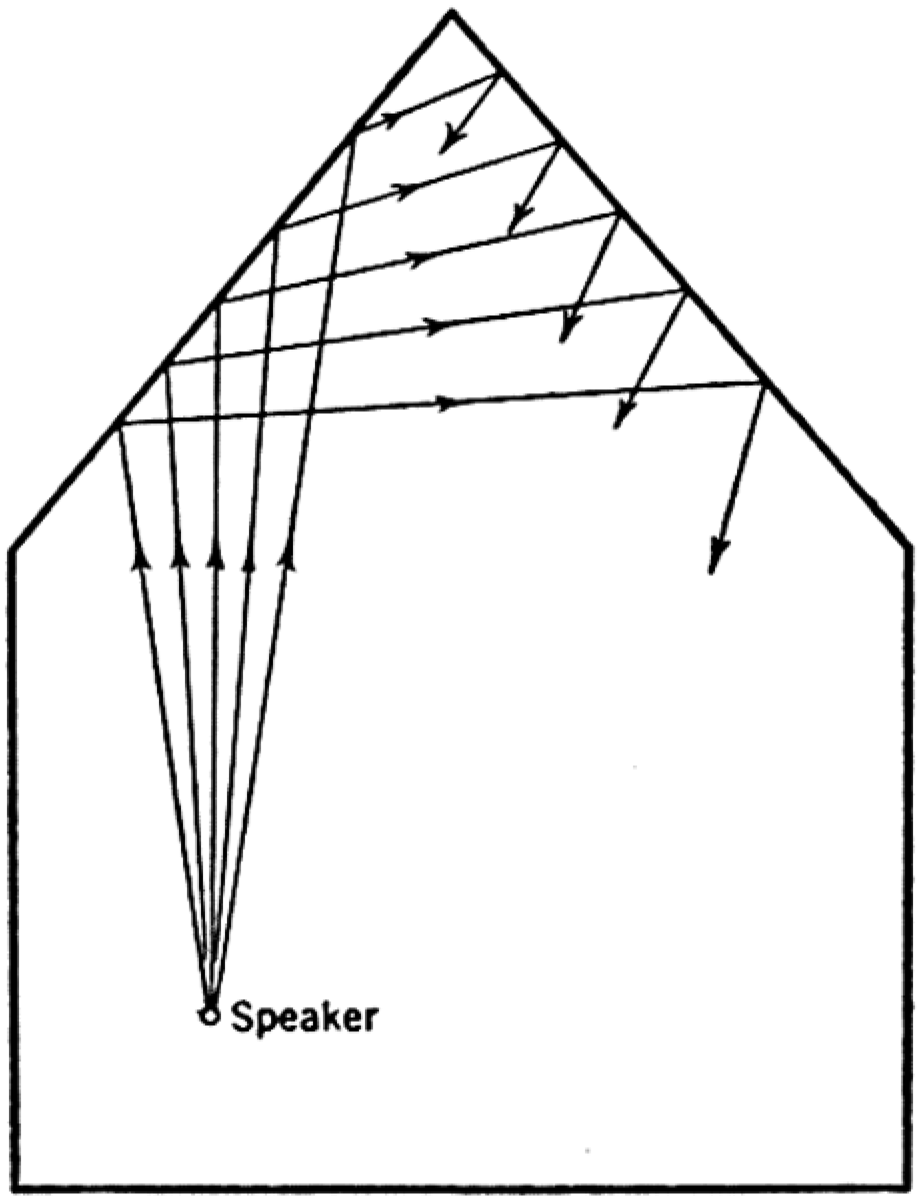

FIG. 8*d*. Absorbing material on this Gothic ceiling is advantageous; sound strikes one ceiling wall and then the other before reaching the auditors, thus giving a double absorption.

Reflections from a Dome Surface. Figure 8*e* pictures the reflections and concentrations of sound that may be expected from a double curvature dome surface. It is much better to have plane or convex surfaces than the concave form shown.

Figure 8*f* shows the amount of concentration of sound by a dome surface compared with a plane surface ceiling of the same height. Problem 5 for Chapter VIII calls for a confirmation of the results shown in this figure.

Sound Absorption. The third very important consideration in the acoustic design of auditoriums concerns the installation of sound-absorbing material to control the reverberation. No acoustical design of a room will be complete or satisfactory without a suitable amount of such material. It is necessary to study the particular conditions of the room to prescribe the amount and kind of material and its location for best effect. Examples of such installations will be given in Chapter IX.

Wires in an Auditorium as a Possible Acoustic Correction. A few words should be written concerning the popular notion that wires and sounding boards are effective in improving faulty acoustics. Experiments and observations show that wires are of practically no benefit when stretched in a room. They scarcely affect the sound, since they present too small a surface to disturb the waves. They have much the same effect on sound waves that a fish line in the water has on water waves. The idea has, perhaps, grown into prominence because of the action of a piano in responding to the notes of a singer. The piano has every advantage over a wire in an auditorium. It has a large number of strings tuned to different pitches, so that it responds

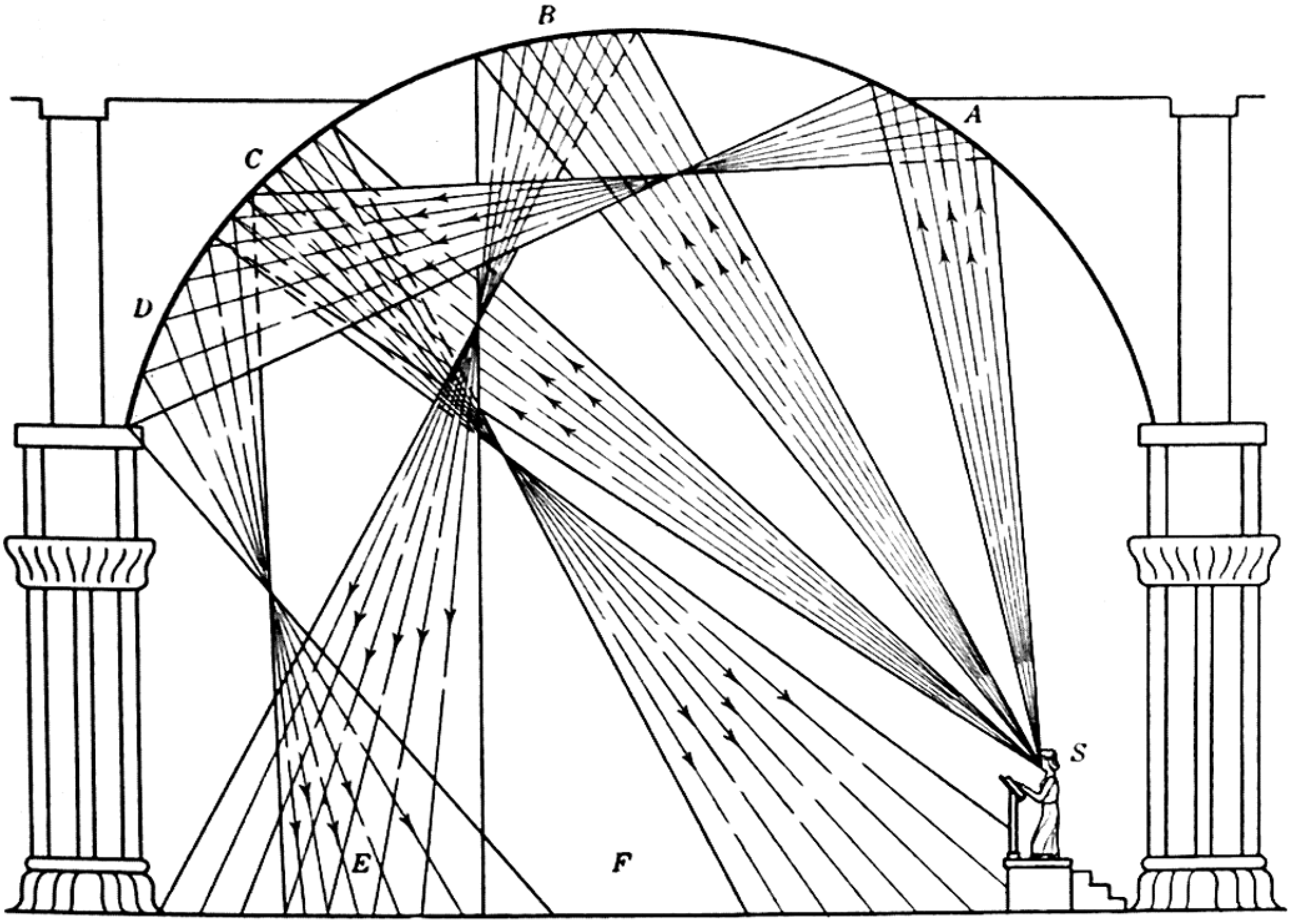

FIG. 8*e*. Objectionable reflections of sound by a dome surface. The distribution of sound in the room is made very uneven, with probable echoes.

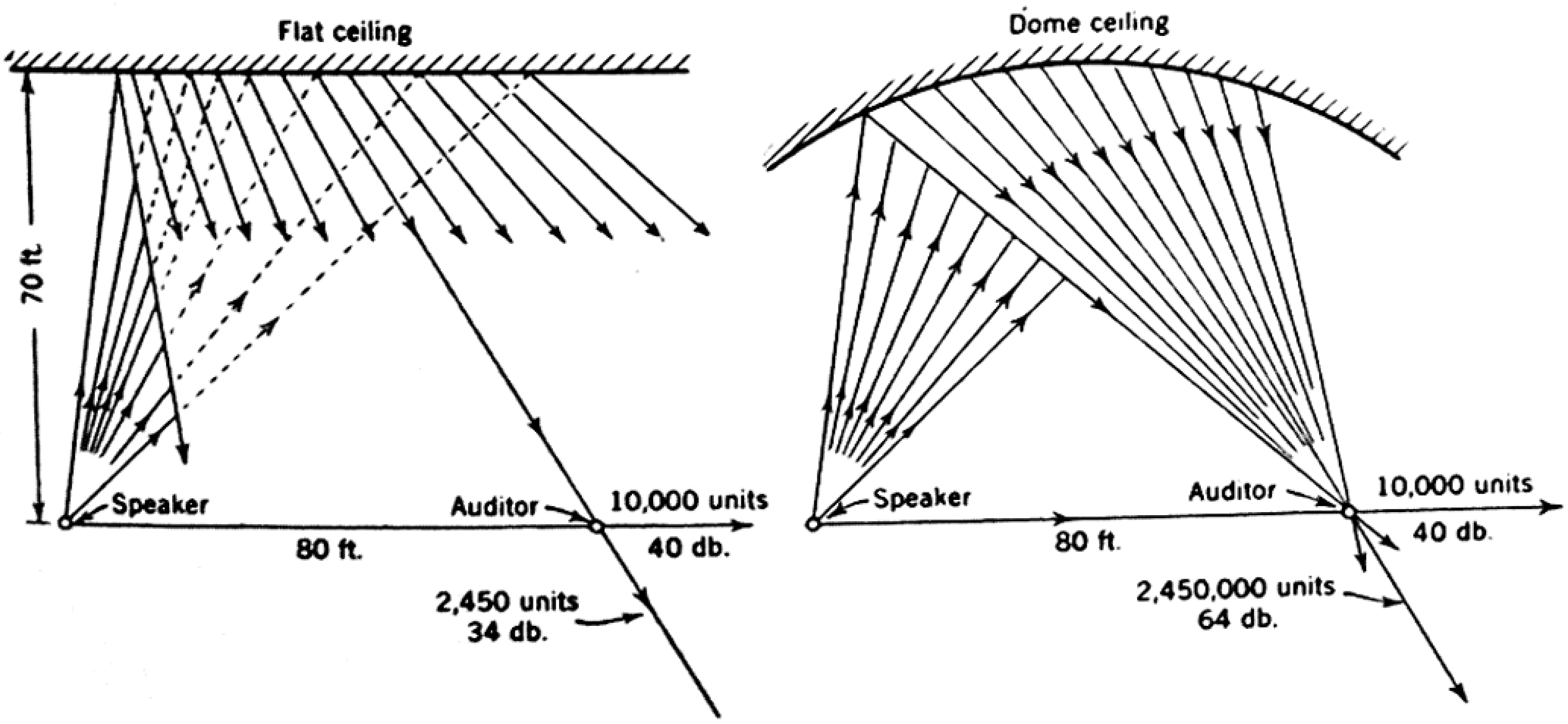

FIG. 8*f*. Diagram showing the concentrations of sound set up by a curved dome ceiling compared with a plane ceiling of the same height.

to almost any note sung; it has also a sounding board that reinforces strongly the sound of the strings; finally, the singer is usually near the piano. A wire stretched in the auditorium responds to only one tone of the many likely to be present; it has no sounding board; and the singer is some distance away. But little effect, therefore, is to be expected. The author has visited a number of halls where wires have been installed and has yet to find one where pronounced improvement has resulted.[1] Sabine[2] cites a hall in which five miles of wire were stretched without helping the acoustic conditions. It is curious that so erroneous a conception has grown up in the public mind with so little experimental basis to support it.

Sounding Boards as an Acoustic Corrective. Sounding boards, or perhaps more correctly reflecting boards, are occasionally of some use but they are never a complete cure for faulty acoustics. When suitably designed and properly placed, they will reflect sound in certain directions, but they do not have the absorbing property needed to reduce the reverberation. Figure 8*g* shows diagrammatically the action of a "sounding" board in directing the reflected sound. In practice, the board need not project so far forward, but it appears desirable to have it extend at least to the edge of the platform.

Figure 8*h* is a photograph of a sounding-board reflector used in an experiment in the investigation of the acoustics of the Auditorium at the University of Illinois. When the speaker stood at the focus of this reflector (a quarter section of a paraboloid of revolution) the sound of his voice was directed in a nearly parallel beam along the axis of the reflector. The device had the advantage that it cut off some sound from the dome and thus avoided some echo effects, but the final correction of the acoustics of the room required the installation of a considerable amount of sound-absorbing materials.

In churches with high ceilings, a plane, inclined reflecting board over the pulpit is recommended; it will cut off some sound from the ceiling, it will reflect sound beneficially to the audience, and it will give the speaker a reassuring resonance. With this arrangement, a sound-amplifying system will constitute an efficient aid for the speaker. The microphone could be placed on the pulpit, but insulated from the woodwork to avoid accidental noises if the pulpit is "pounded." The loud-speaker of the system could be mounted on top of the reflecting board, but concealed from the audience by a porous drapery that would allow easy passage of the sound.

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[1] *Science*, Vol. 35, p. 833, 1912.

[2] *Arch. Quarterly* of Harvard University, March, 1912.

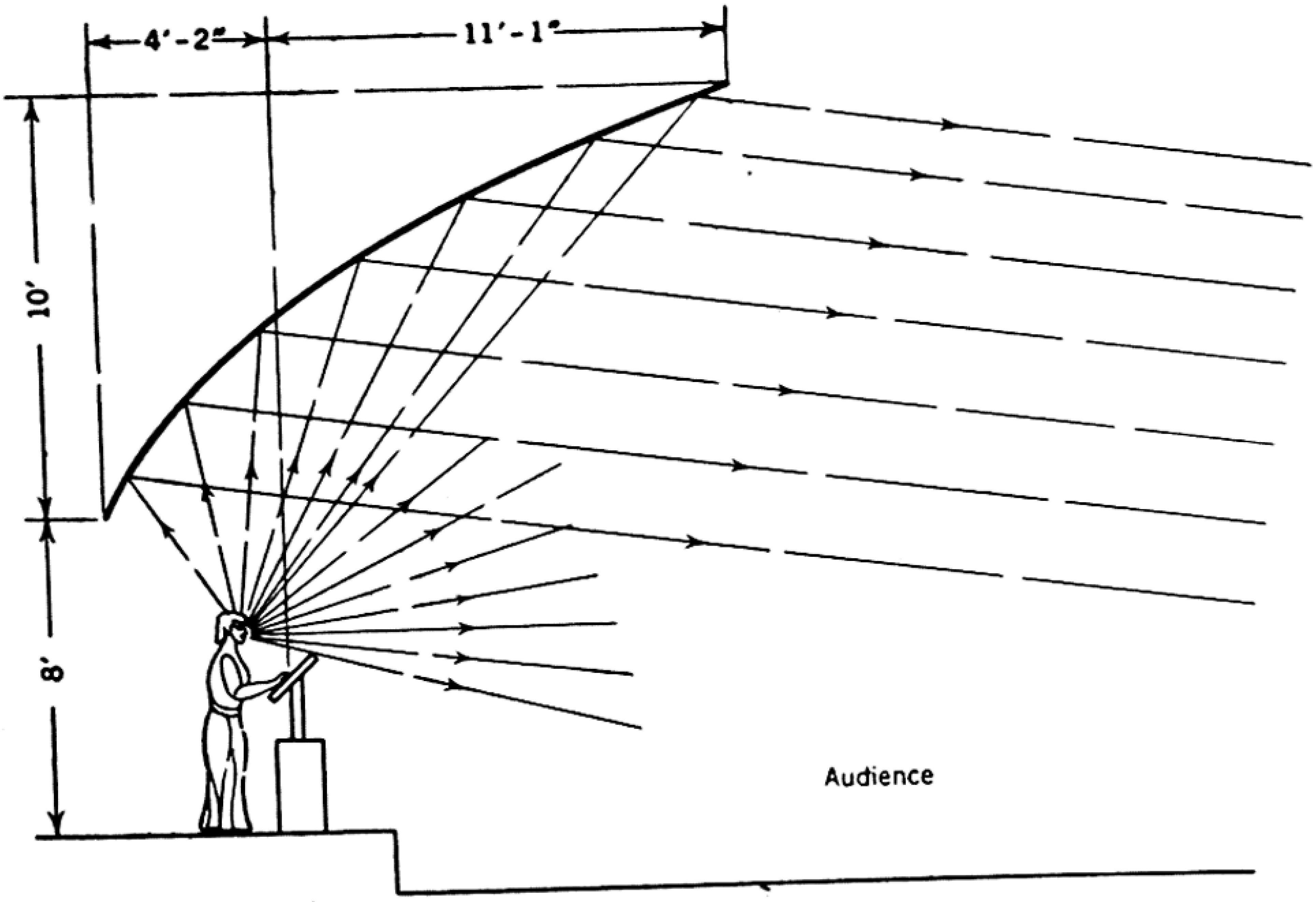

FIG. 8*g*. Sketch showing how a "sounding" board reflects sound.

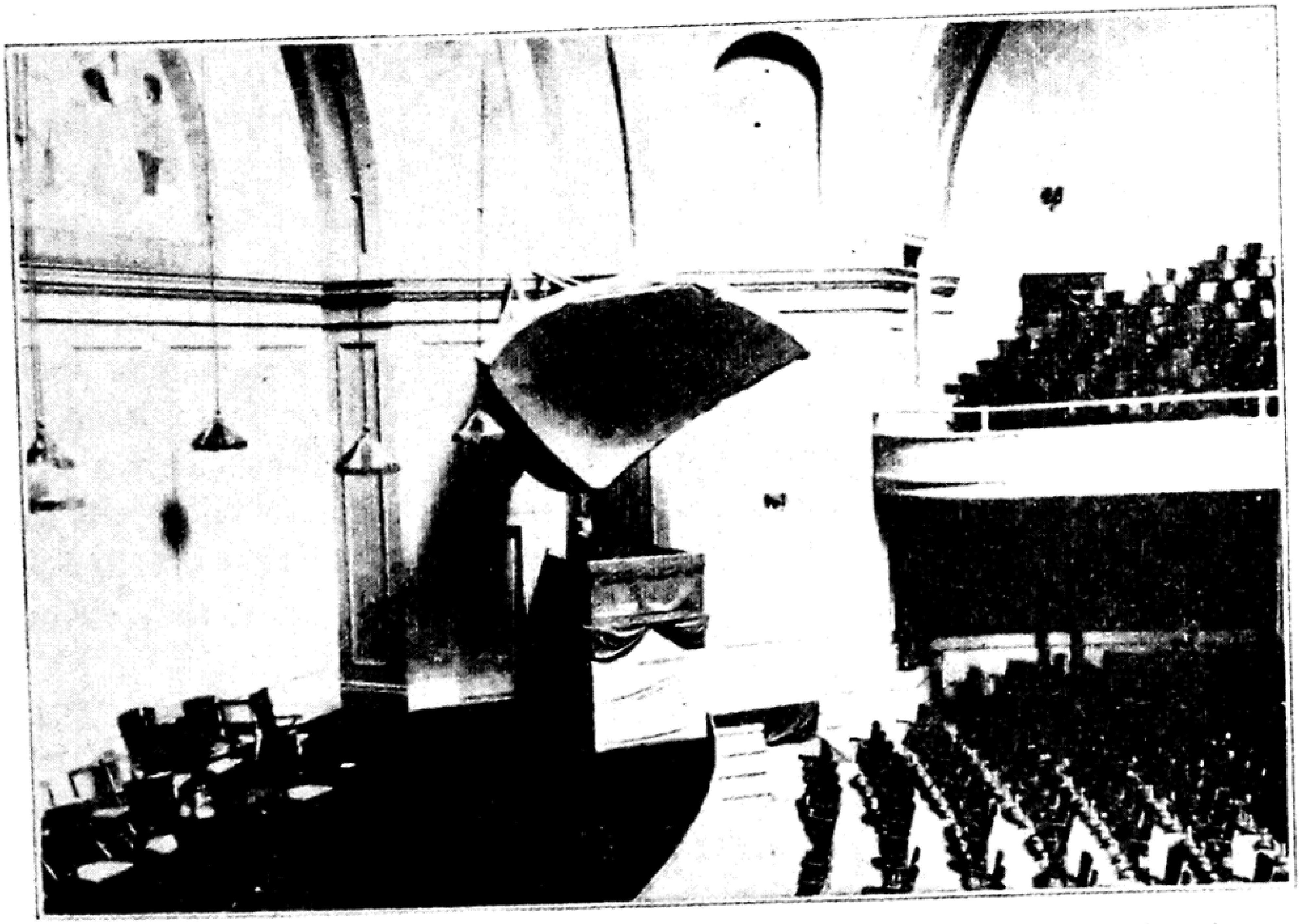

FIG. 8*h*. Sounding board reflector used in the University of Illinois Auditorium. It did not correct the acoustics.

Modeling New Auditoriums after Old Ones with Good Acoustics. Another suggestion often made is that architects should model auditoriums after those already built that have good acoustic properties. It does not follow that halls so modeled will be successful, since the materials used in construction are not the same year after year. For instance, years ago it was the usual custom to build wooden structures and apply plaster on wood lath; now the modern constructions are usually made of more rigid steel and concrete with metal lath, thus presenting surfaces to the action of sound that are quite different in effect. Furthermore, a new hall usually is changed somewhat in form from the old one, to suit the ideas of the architect, and it is very likely that the changes will affect the acoustics.

Effect of the Ventilation System. It would seem at first thought that the ventilation system in a room would affect the acoustics. The air is the medium that transmits the sound, and it has been shown that the wind has an action in changing the direction of propagation of sound. Sound is also reflected and refracted at the boundary of gases that differ in density and temperature. Practically, however, it is found that the effect of the usual ventilation currents on the acoustics in an auditorium is small. The temperature difference between the heated current and the air in the room is not great enough to give an appreciable effect, and the motion of the current is too slow and extends over too short a distance to change the action of the sound to any marked extent.

Under special circumstances, the heating and ventilating systems may prove disadvantageous. A hot stove or a current of hot air in the center of the room will seriously disturb the action of the sound. Any irregularity in the air currents that causes alternate sheets of cold and heated air to be set up will modify the regular progress of the sound and produce confusion. The object to be striven for is to keep the air in the room as homogeneous and steady as possible. Hot stoves, radiators, and currents of heated air should be kept near the walls and out of the center of the room. It is of some small advantage to have the ventilation current go in the same direction as the sound, since a wind tends to carry the sound with it.

Conclusion. The preceding discussions present some of the principles applied in the acoustic design of auditoriums. The explanations in this chapter are supplemented throughout the text by various illustrations of the principles set forth; also there will be found additional suggestions that will be helpful in solving special problems.

CHAPTER IX

EXAMPLES OF ACOUSTIC DESIGN AND CORRECTION

Types of Rooms. It is the purpose in this chapter to describe examples of acoustic treatment in different types of rooms, with comments on the acoustic conditions that should prove helpful to the reader in the design or correction of other rooms. These examples will show rooms with volumes both large and small, with high ceilings and low ceilings, rooms of various shapes with curved walls, domed ceilings, etc.

Offices. Generally, in small rooms, the acoustic problem is to control noise rather than reverberation as in large rooms. Usually acoustic treatment is applied to the ceiling. See Chapter XIV, which discusses the acoustic adjustment of this type of room.

Rooms with High Ceilings. If the ceiling of a room is rather high, as in many church auditoriums, it is quite necessary to treat the side walls acoustically so as to reduce the disturbing horizontal reflections. It has been common practice to consider acoustic treatment of ceilings as the logical procedure, but recent advances indicate that frequently it is more important to consider the side-wall quieting first because there is usually little absorption to reduce the horizontal reflections, whereas the vertical reflections are always subject to the absorption of the seats and the audience. Figure 9*a* shows a church auditorium in which the necessary side-wall treatment brought good acoustics.

Small Church Auditorium. A church auditorium with a seating capacity for 500 is shown in Fig. 9*b*. It was designed primarily for speaking, but it is used also for vocal music on the stage and for instrumental music by an orchestra in front of the stage. The acoustical treatment consists of sound-absorbing board installed on the ceiling, which appears to be insufficient for optimal conditions, as shown later. It was feared that an echo would be set up by the large rear wall, but the fear was not realized, probably because of the absorption of the ceiling and the obstruction furnished by the wooden trusses and the absorption by the audience. Sound passing to the ceiling strikes one slant side and passes to the other side before being reflected to the floor. See Fig. 8*d*. Sound reflected from the rear wall would experience this double reflection and absorption, any echo effect being thus reduced.

A specially arranged sound-amplifying system has proved to be very helpful in securing better acoustics. One microphone on the stage picks up all sounds of music and speech and carries them to the hard-of-hearing outlets and to a loud-speaker in an " overflow " room used when audiences are too large to be accommodated in the main auditorium. A second microphone is used only to amplify speaking from the pulpit. It is put in operation by a " silent " key by the speaker when he starts to talk and thus actuates a loud-speaker that directs the amplified sound to the audience in the rear half of the church, but it also carries sound to the hard-of-hearing and the overflow room. This system does not amplify the music through the auditorium loud-speaker, an arrangement preferred by musicians who think that the music has sufficient volume and are fearful that the amplifying system will distort the music. The use of an amplifying system is a great aid to a speaker. The amplification fills the room with vibrant sound that allows him to hear himself and thus inspires him to use his amplified voice to impress the audience.

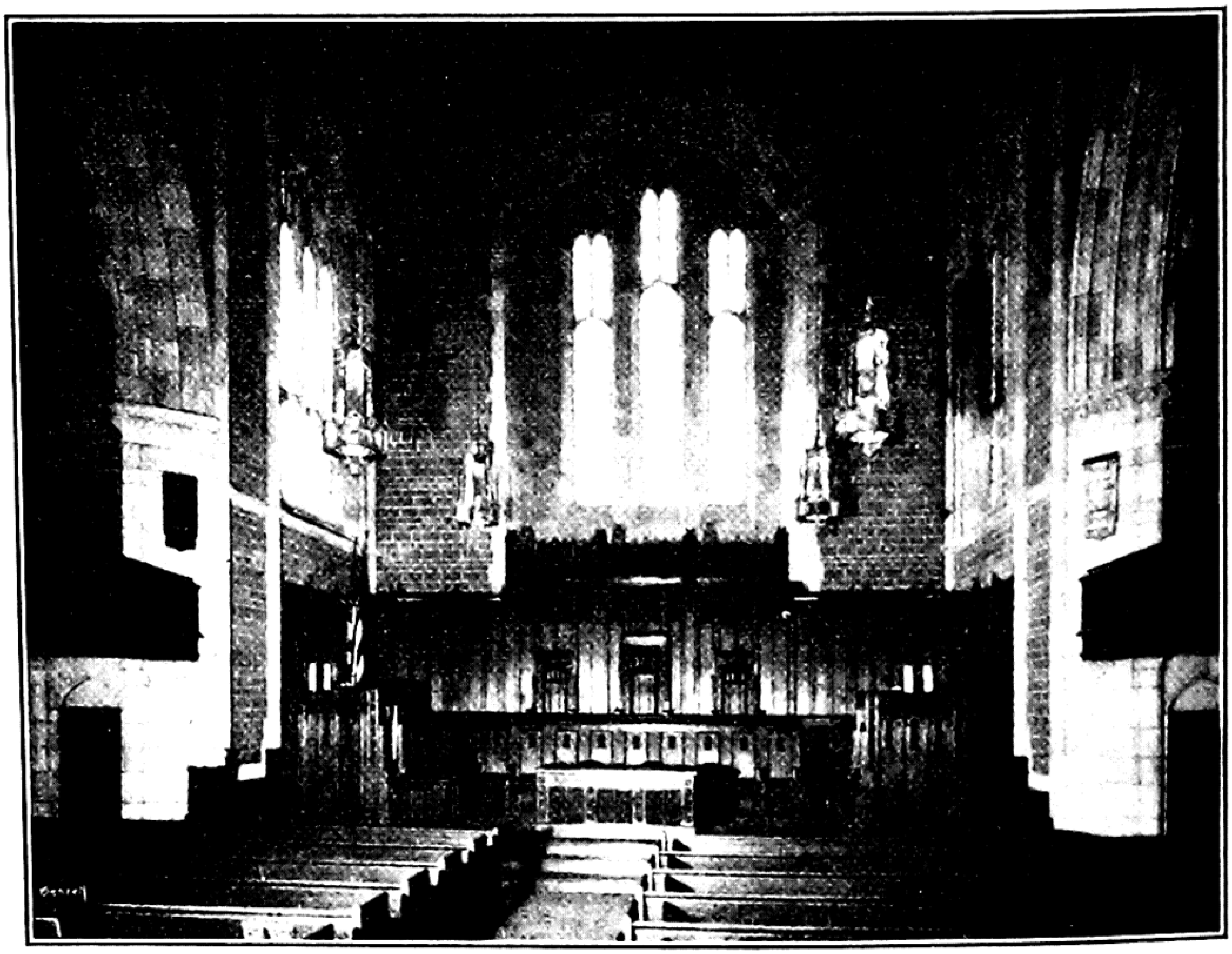

Fig. 9*a*. Acoustical treatment of the side walls of this high-ceilinged church proved beneficial. (Bryn Mawr Presbyterian Church, Karcher & Smith, Architects.)

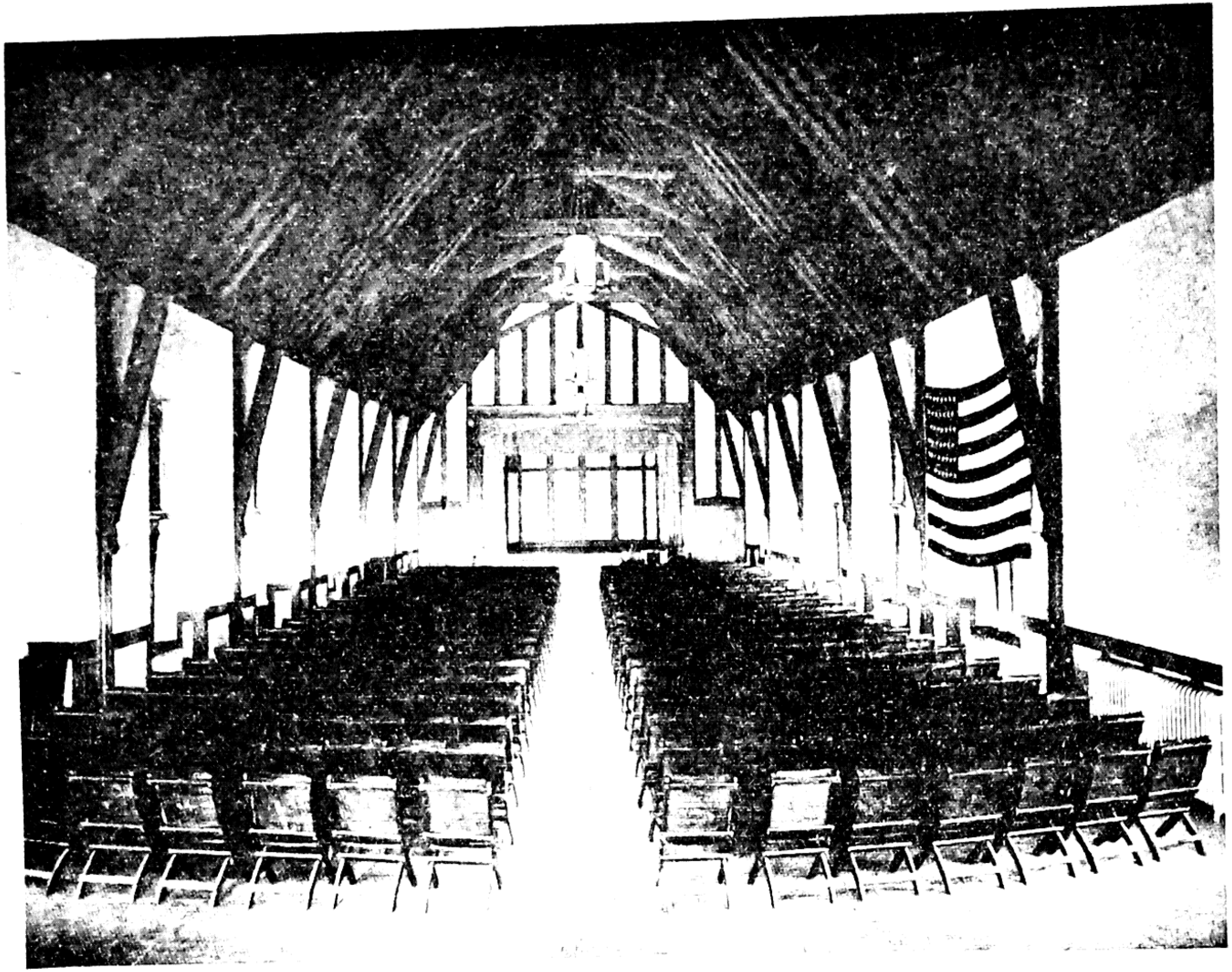

FIG. 9*b*. Acoustical treatment of the two slant ceiling walls gave the double absorption, shown in Fig. 8*d*.

The calculations for the acoustical correction follow. The volume of the room is 101,000 cubic feet, and the optimal time of reverberation from Fig. 6*b* is taken as 1.3 seconds as an average. The absorbing values are set forth as follows:

MATERIAL	AREA, square feet	COEFFICIENT	ABSORPTION (as)	
Plaster	3,260	@ 0.025	82 sabins	
Wood	10,600	@ 0.03	318 "	
Concrete	3,790	@ 0.015	57 "	
Acoustic board	3,000	@ 0.3	900 "	
Curtains	200	@ 0.1	20 "	
Seats	500	@ 0.24	120 "	
Approximate total (as) for empty room			1500 "	
200 auditors (4.24–0.24), add			800 "	2300 sabins
500 auditors " add			2000 "	3500 "

Time of reverberation: $t = 0.05V/(as)$

t (empty room) $= 0.05 \times 101{,}000/1500 = 3.36$ seconds
t (200 audience) $= 0.05 \times 101{,}000/2300 = 2.2$ "
t (500 audience) $= 0.05 \times 101{,}000/3500 = 1.44$ "

These times show that the optimal value of 1.3 seconds is not reached even with the maximum audience of 500 people. To get optimal conditions, it is necessary to add more absorption. The value of the absorption needed is found by the equation: $(as) = 0.05\ V/1.3$, or 3,880 sabins. Since the empty room plus the average audience gives 2,300 sabins, there must be added the difference, or 3,880 − 2,300 or 1,580 sabins. This additional absorption could preferably be installed on the side and rear walls. Summing up, it might be said that this room is characteristic of many rooms that are partly corrected; they are not noticeably bad acoustically, but the hearing conditions are not optimal.

Small Lecture Room. Figure 9*c* portrays the interior of a physics lecture room with a volume of 37,000 cubic feet and with 260 seats. This room was first adjusted for the optimal time for speaking for a room of this size by applying sound absorbent to the side and rear walls, and in the coffers about the central skylight. With this arrangement, students in all locations in the room could understand the lecturer. However, when an amplifying system was used for some experiments in sound, the students approved the amplification so much that the system was used for all the lectures. This experience illustrates the desirability of having the sound level of speech in a room with a value of about 60–70 decibels, in addition to having an optimal time of reverberation. The louder sound holds the attention of the audience and is beneficial for those who are hard of hearing.

Small Concert Hall. A concert hall should be somewhat more reverberant than a lecture room. The auditorium pictured in Fig. 9*d* is one unit in the Eastman School of Music, given by Mr. George Eastman to the city of Rochester, New York. Messrs. Gordon and Kaelber were the architects, with McKim, Mead, and White as associate architects. After a year of use for chamber music, solos, and lectures, reports state that the "acoustics are perfect." The shape of the hall is rectangular, with the floor rising rather steeply toward the rear. Possible echoes from the ceiling are minimized by means of coffering and ventilation grills. Reflections from the rear wall are eliminated by the tier of sloping seats. Side-wall reflections are reduced by the rather large sections of plush curtain material. The small volume of the room makes it suitable for light music, such as vocal and instrumental solos. It is also adapted for chamber music,

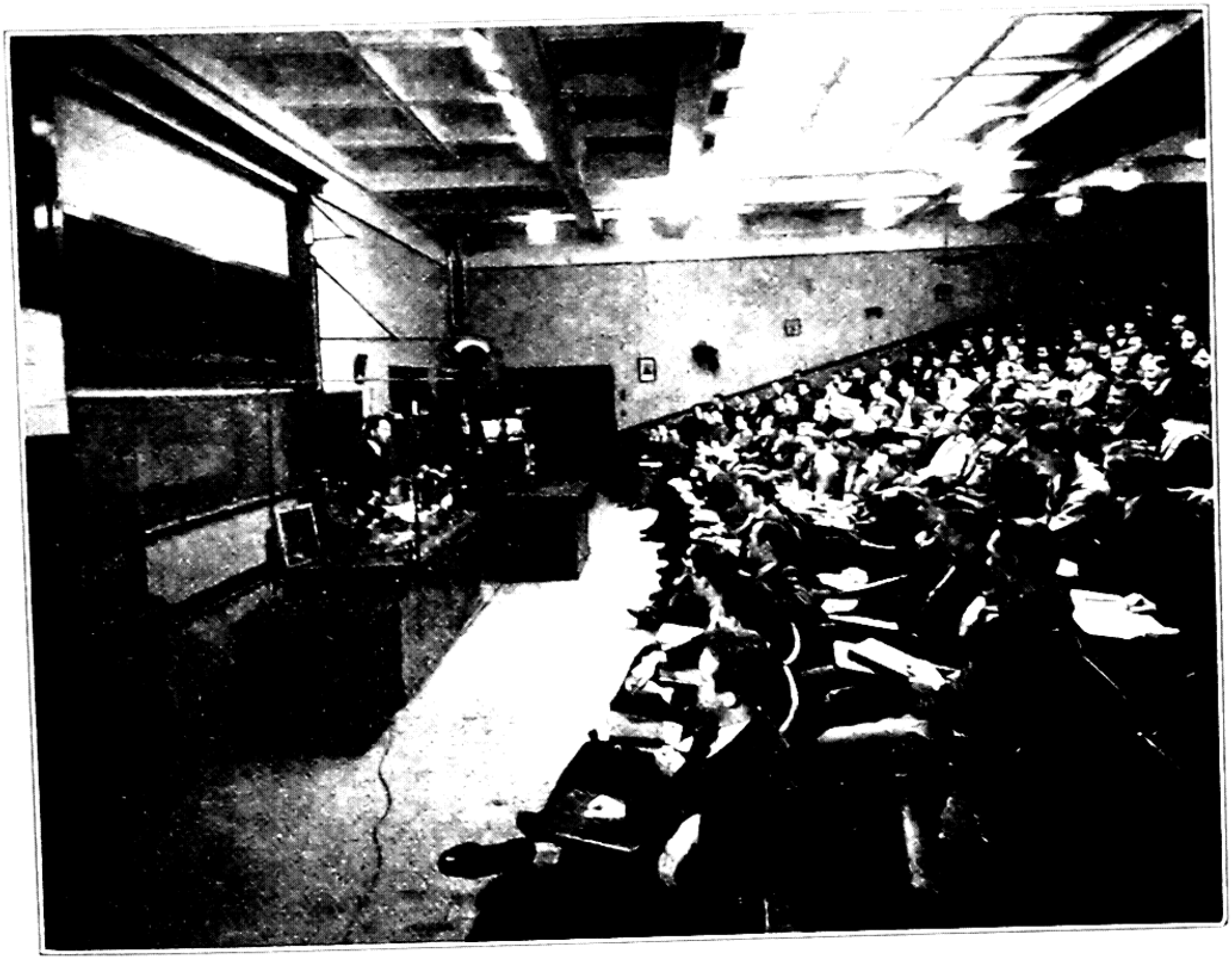

FIG. 9*c*. Lecture room at the University of Illinois. A public-address system added much to the ease of understanding speech, although the room had already been adjusted with absorbing material to give the usual optimal reverberation.

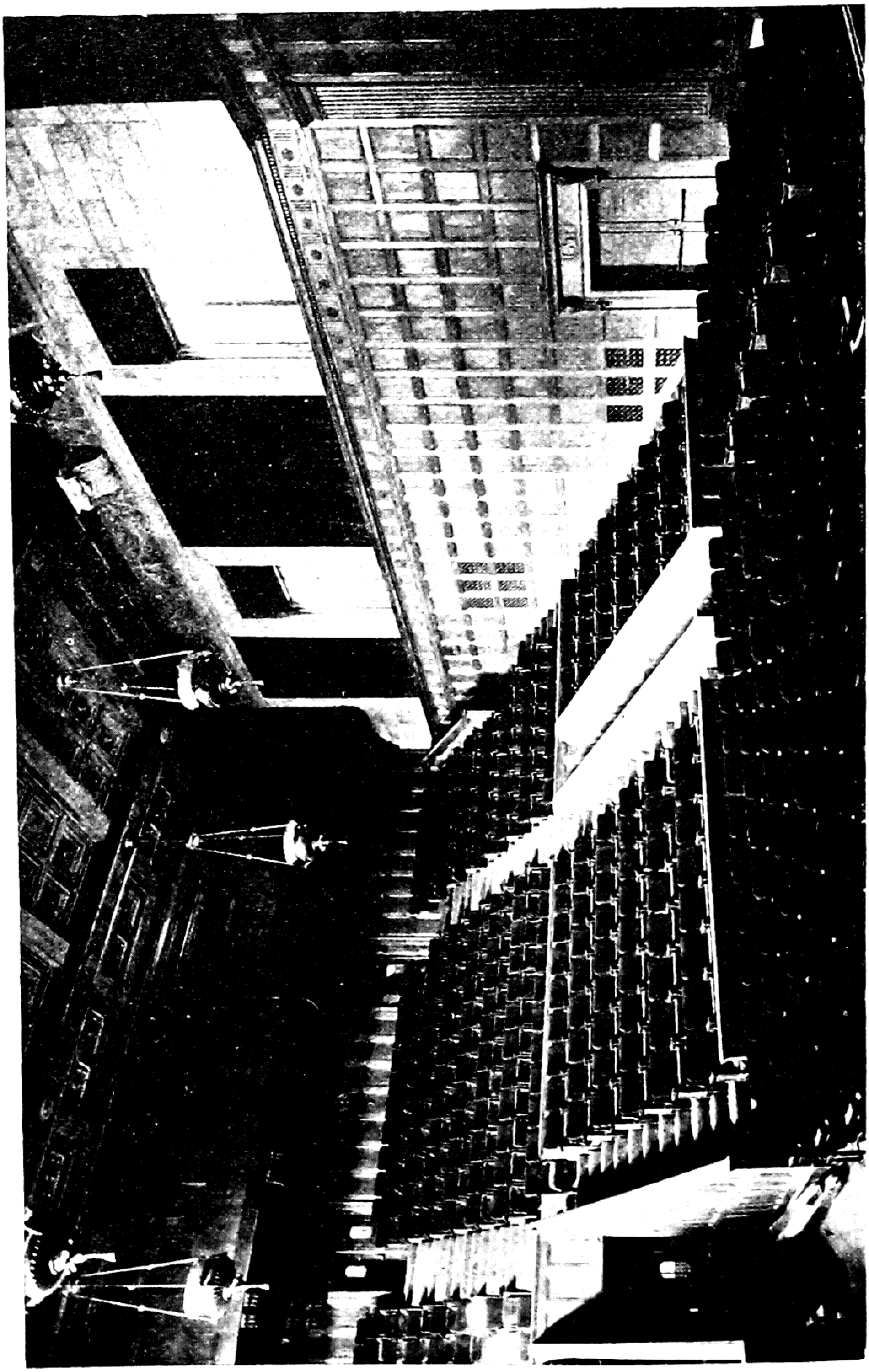

FIG. 9*d*. Kilbourn Hall at the Eastman School of Music. The sloping bank of upholstered seats is largely responsible for the good acoustics in this hall. The wood paneling produces interesting resonances.

but not for heavy orchestras. The considerable area of woodwork in this room affects the musical quality, reinforcing various tones.

The acoustical data are given in the following tabulation:

Wood paneling	9,533 sq ft	at 0.06	=	571 sabins	
Art stone	3,365 " "	at 0.02	=	67 "	
Carpet (lined)	2,546 " "	at 0.35	=	892 "	
Curtains	780 " "	at 0.50	=	390 "	
Glass	200 " "	at 0.027	=	5 "	
Vents	669 " "	at 0.50	=	334 "	
Upholstered seats	506 " "	at 2.5	=	1,265 "	
Total absorption with no audience				3,524 "	
Audience (200) at (4.5 − 2.5 = 2)			=	400 "	3,924 sabins
Audience (506) at (4.5 − 2.5 = 2)			=	1,012 "	4,536 "

Volume of room = 140,000 cu ft; optimal time = 1.6 seconds;
$(as) = 0.05 \times 140{,}000 \div 1.6 = 4{,}370$ sabins

The room thus appears too reverberant for an audience of 200, but satisfactory for large audiences.

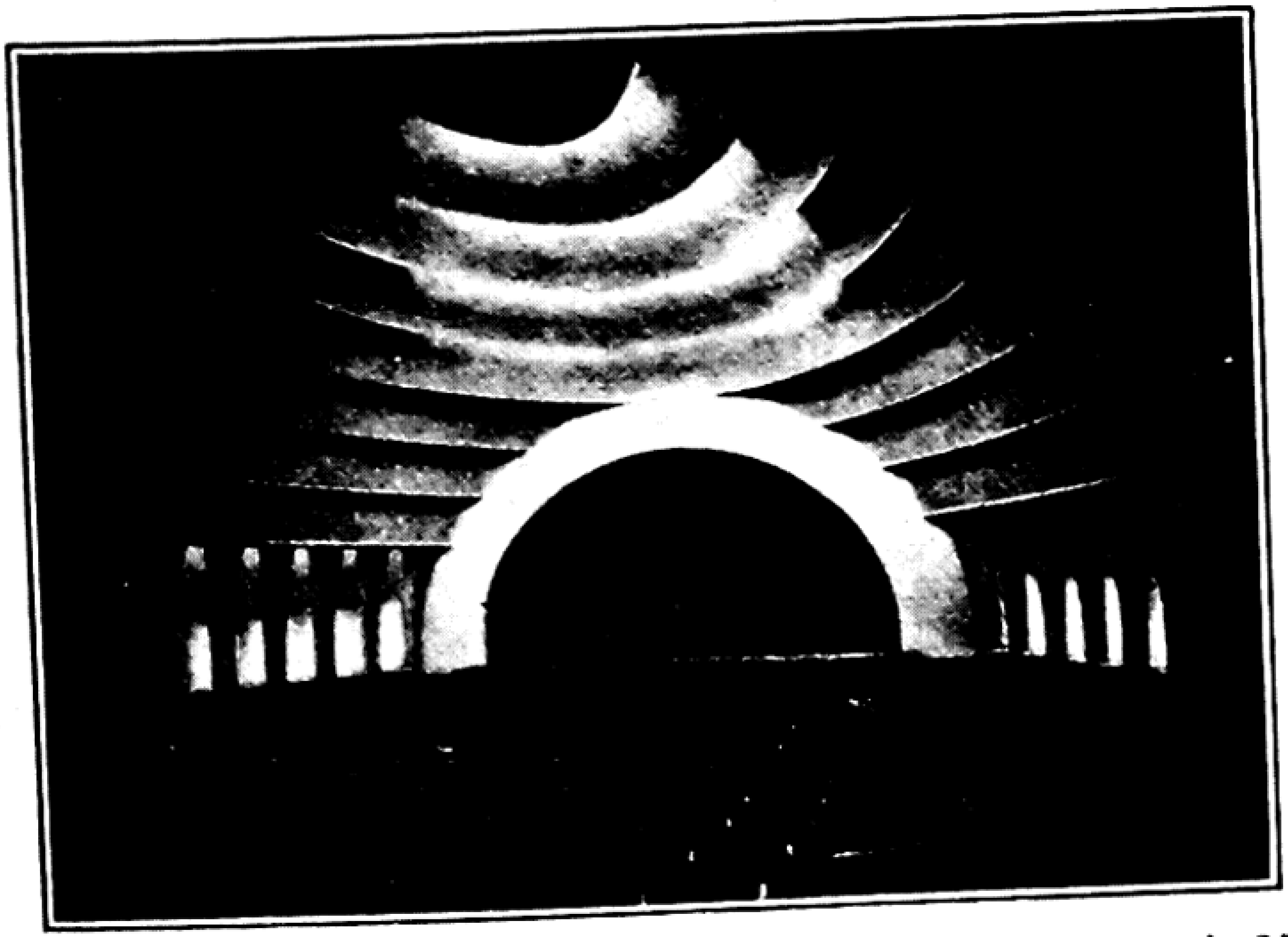

FIG. 9*e*. The hung plaster ceiling of this room was perforated with 25 per cent of grillwork to eliminate focusing of sound by the curved surface. (Auditorium, New School of Social Research, New York City. Joseph Urban, Architect.)

Auditorium with Curved Walls. Figure 9*e* exhibits a small auditorium with a shape that is roughly elliptical, cut off at the base by the floor. Ordinary treatment would not stop the concentrations of sound reflected from the curved walls, so that a drastic procedure was followed: the entire curved ceiling was made of grillwork with 25 per cent perforations! The architect very cleverly adapted this unusual con-

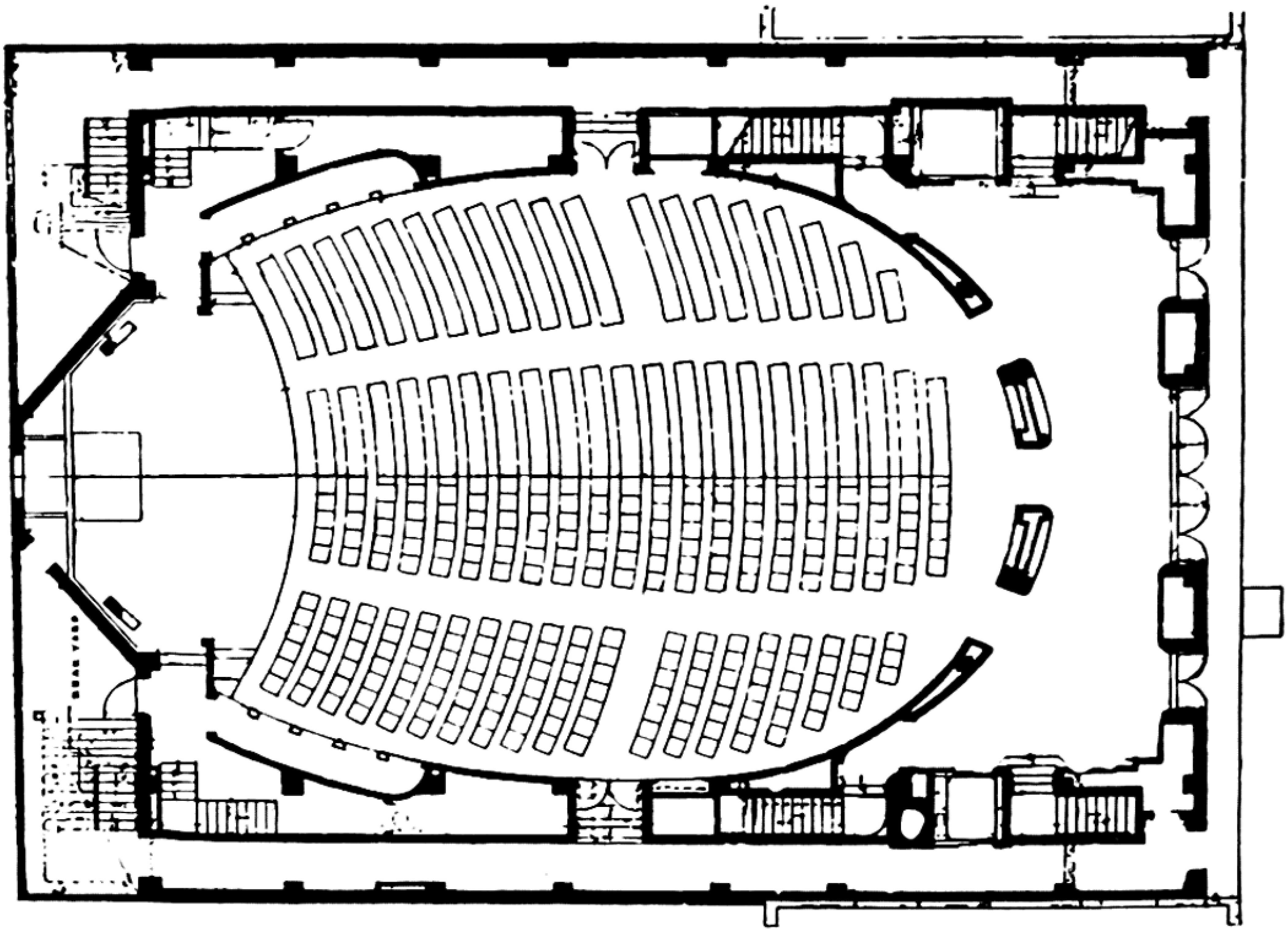

FIG. 9*f* (*a*). Plan of the auditorium shown in Fig. 9*e*.

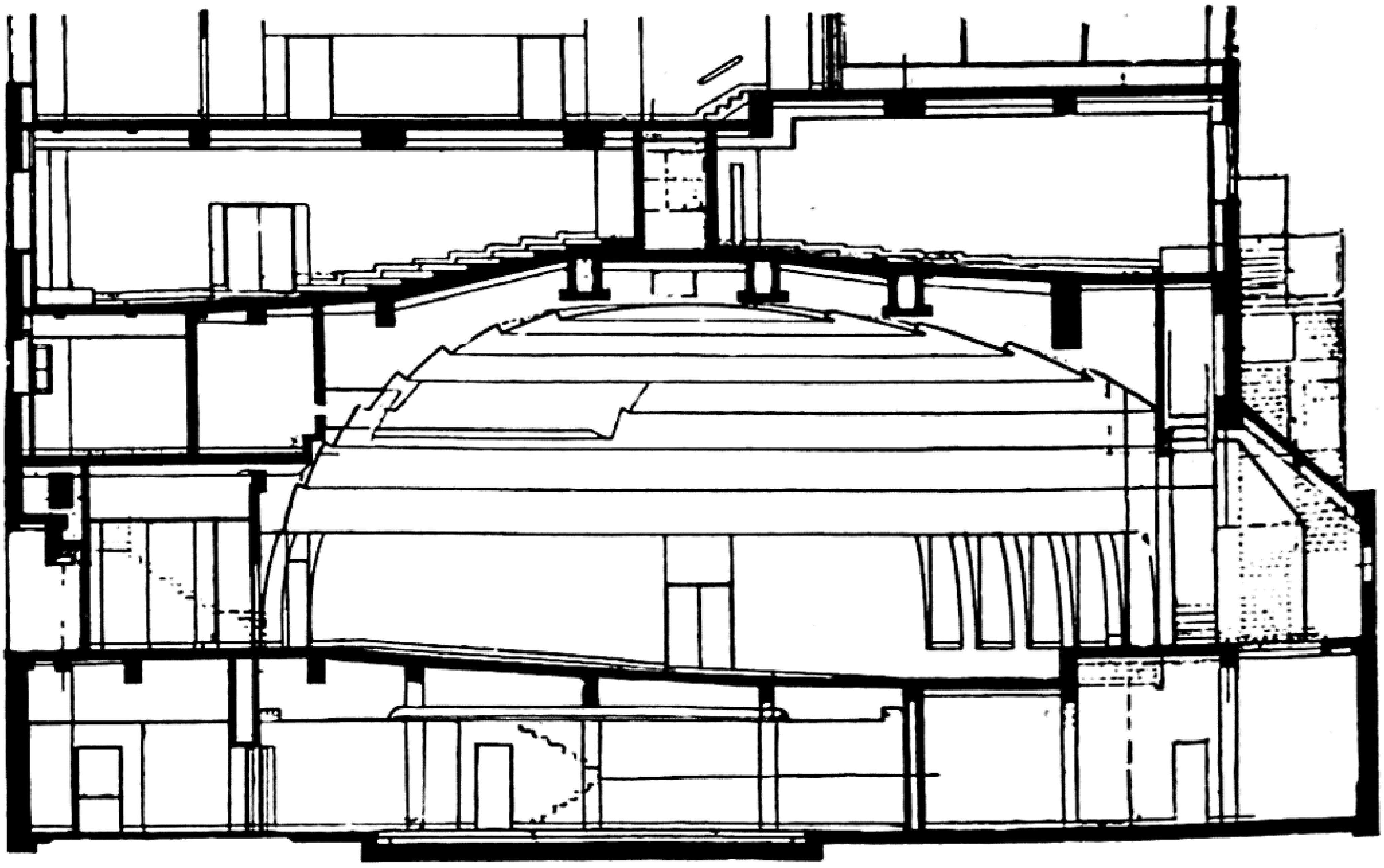

FIG. 9*f* (*b*). Section of the auditorium shown in Fig. 9*e*.

struction into a decorative scheme of ellipses, which allowed opportunity for ventilation and for projection of lights to the stage.

Figure 9*f* shows the plan and section of the room. The curved side walls adjacent to the stage were broken by arches opening into the passageway. Upholstered seats furnished the material for absorption of sound, and heavy curtains were to be hung from the rear side walls if necessary to control reflections from these surfaces. The outcome for the acoustics was satisfactory and speaking could be heard and understood easily, without a disturbing focusing of sound.

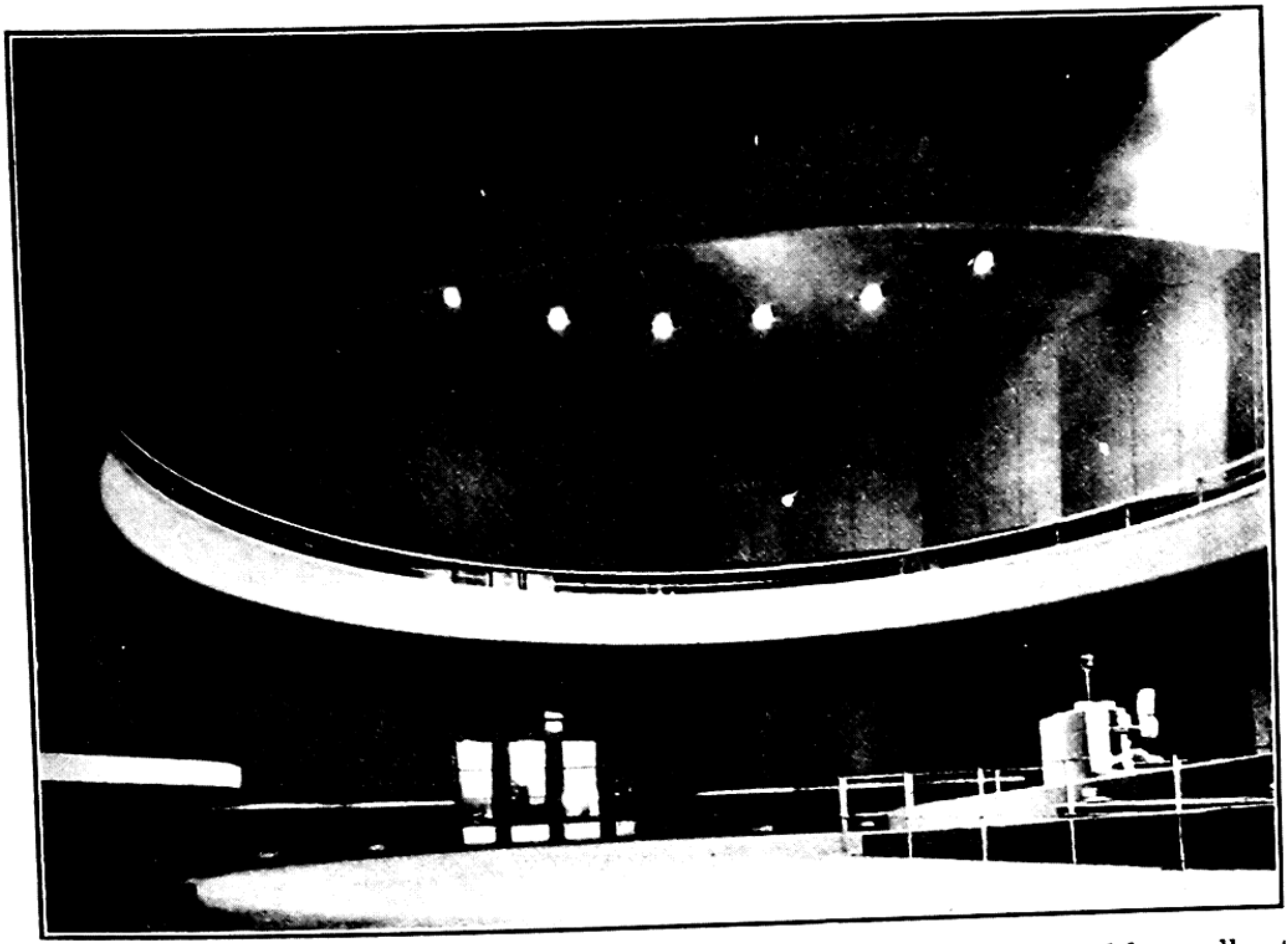

FIG. 9*g*. Voder Room, New York World's Fair. Acoustically adjusted by walls of special shape, with suitable absorbing materials. (Photograph by John Mills.)

Convex Curved Wall Treatment. Figure 9*g* shows the Voder Room at the New York World's Fair that had an unusual shape and needed unusual acoustic correction. A cylindrical outline form, averaging 75 feet in diameter and 40 feet in height with provision for a circular balcony, was selected as the most desirable shape for the visual presentation of the Voder. Through the use of tilted walls and convex curvatures, the interior form of the room was developed to eliminate focusing effect and to control the destination and dispersion of sound reflections. Perforated board was used as the finishing material for the wall surfaces, although much of the area behind the board remained untreated so as to avoid too much absorption. The time of reverberation from 50 to 10,000 cycles was 1 second within a small variation.[1]

University of Illinois Auditorium. The large number of curved walls in this room and the consequent echoes formed were described in detail

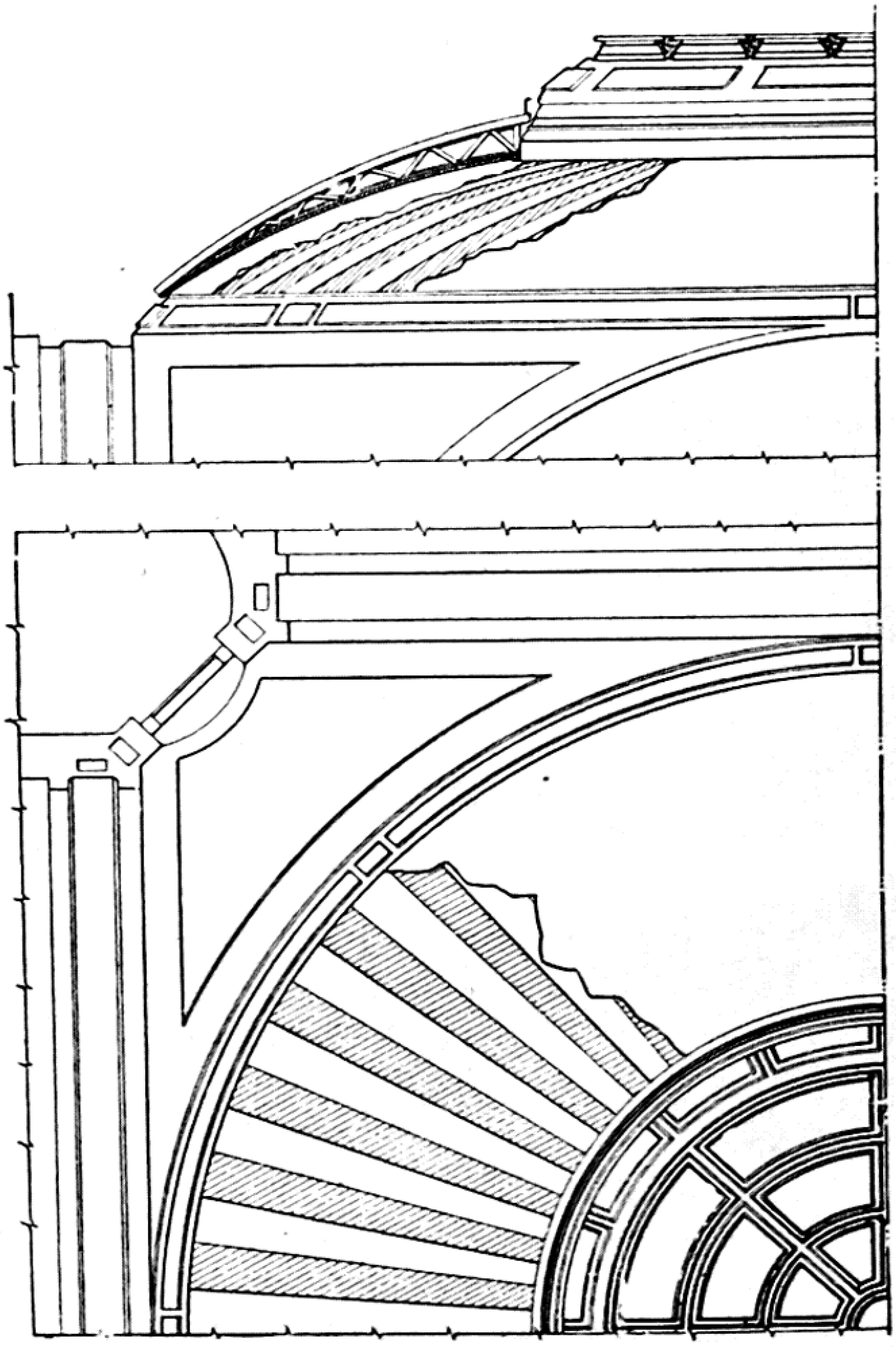

FIG. 9*h*. Acoustical treatment of the dome surface of the University of Illinois Auditorium with radial strips of material mounted out from the ceiling surface.

in *Bulletins* 73 and 87 of the University of Illinois Engineering Experiment Station. Recently, the auditorium was redecorated and some necessary changes were made in the acoustical correction. The hairfelt with muslin covering used originally was removed, because the installation was dirty and unsightly, and it had become a fire hazard. The previous arrangement of acoustic materials that proved so effective in reducing the focusing of sound by the dome ceiling was retained. The radial wooden ribs, that extended 18 inches down at the edge of the skylight and gradually approached the curved ceiling, meeting it at the lower circle of the dome, were kept. See Fig. 9*h*. Radial strips of rock wool 2 inches thick replaced the original hairfelt and were attached to the under side of these ribs, stretching across between two adjacent ribs, with bare spaces and no rock wool between the ribs on either side. This arrangement of rock wool alternated with bare spaces served effectively to absorb and diffract the sound so that any echoes were greatly reduced. For decorative appearance, this construction was covered with completely perforated Celotex squares, 12 inches by 12 inches, nailed to circular, horizontal wood stripping. See Fig. 9*i*. To avoid gaps at the outer circle, some of the squares were cut to fit. The perforated Celotex allowed easy access of sound to the rock wool beneath. Rock wool replaced the hairfelt on the curved side walls, where it also was covered with the completely perforated Celotex. Additional absorption was obtained by using upholstered seats and by installing absorbing material on the soffit of the balcony. This new acoustical arrangement improved the acoustics over the previous treatment, although some echoes are still detectable at times, as was expected, because the curved walls could not be changed.

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[1] C. C. Potwin and J. P. Maxfield, *Jour. Acous. Soc. Amer.*, Vol. 11, p. 48, 1939.

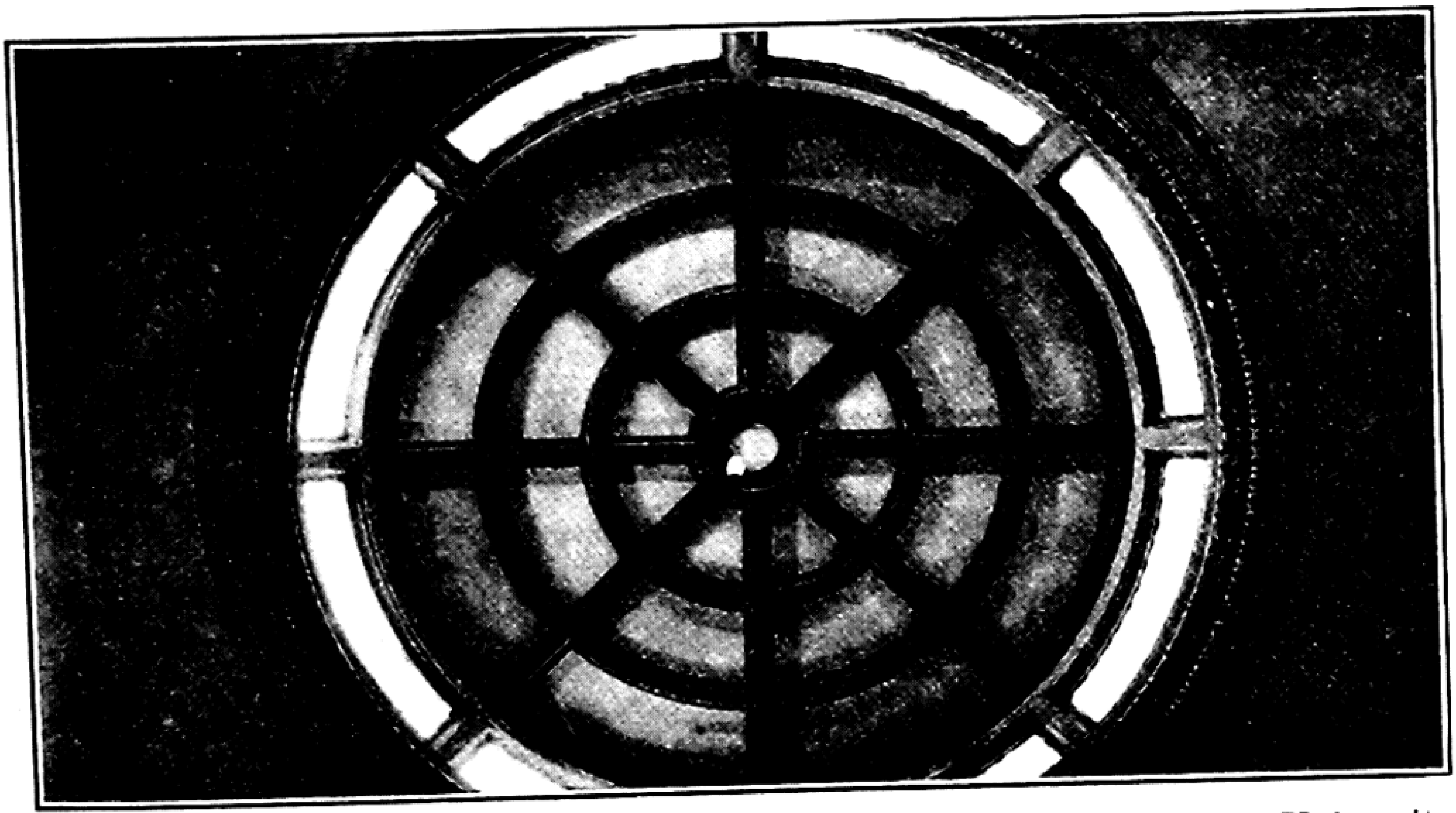

FIG. 9*i*. Photograph of skylight and acoustically treated dome of the University of Illinois Auditorium.

Acoustics of the National Gallery of Art. The acoustical problems presented in the National Gallery of Art are unusual and difficult of solution because the formal, memorial character of the building is best fulfilled by the extensive use of ornamental stone, which has very little sound-absorbing efficiency. As a result it was evident in the beginning that the gallery rooms would be reverberant except where provision could be made to absorb sound. For example, the interior surfaces of the Exhibition Galleries were decided by the period and style of the paintings and objects of art to be exhibited, and these restricted the choice of materials. It was therefore necessary to withhold installing acoustical materials in certain rooms where they did not accord with the decorative stone, and such spaces were, of course, reverberant. It should be remarked, however, that visitors in art galleries are supposed to be quiet, so that normally there would not be much sound to be absorbed, and the use of sound absorbents would not be so necessary as in other types of buildings.

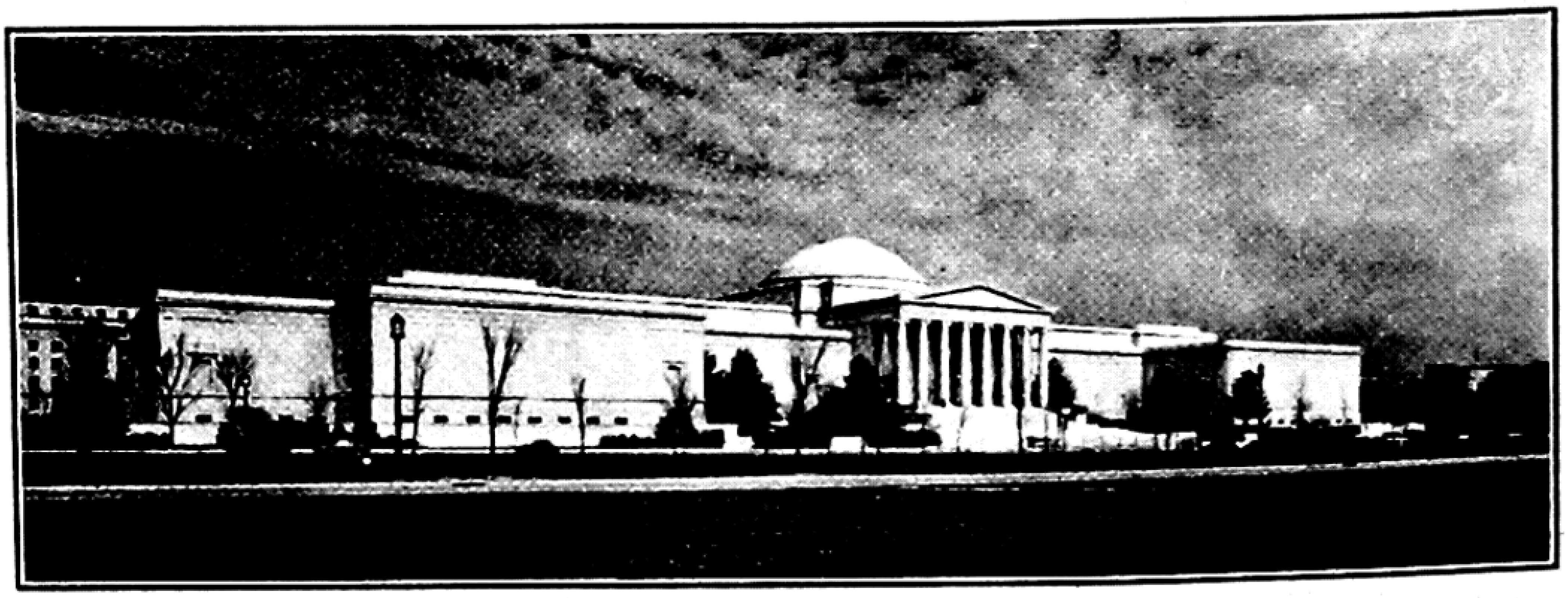

FIG. 9j. National Gallery of Art, Washington, D. C. (Architects: John Russel Pope, 1874–1937; Associates, Otto R. Eggers and Daniel P. Higgins. Photograph by Samuel H. Gottscho.)

Recommendations for sound quieting were approved where they were architecturally allowable. Thus the dome of the rotunda was broken by coffering, and the central unit of each coffer was equipped with a special sound-absorbing construction. The ornamental balcony of the rotunda was covered with absorbing material on surfaces not visible from the floor. The vaulted ceilings of the east and west central galleries were lined with absorbent plaster to reduce reverberation and echoes, and similar action was taken for the small galleries with dome ceilings. The ceilings of the entrance were coffered, with absorbing plaster prescribed for each unit. On the ground floor, where the architectural restrictions were not so severe, the acoustic difficulties were corrected more completely. The lecture hall was adjusted acoustically in accordance with the latest technique. Various rooms to be used for offices, conferences, and clerical work were quieted in the usual manner.

Machines on the lower floor, pumps, ventilating fans, and similar equipment were isolated with cork foundations, and the rooms housing them were acoustically treated. Ventilation ducts were lined, where necessary, to deaden any objectionable transmission of noise.

Purdue Music Hall. This building was planned to care for University commencements, conferences, musical entertainments, sound motion pictures, and other, miscellaneous meetings. Since large audiences were expected, the auditorium was made large, with 6,208 upholstered seats on the main floor and the two balconies. The main auditorium measures 166 feet in width and 156 feet from the back row of seats to the proscenium opening. The stage opening is 100 feet wide and 37 feet high. A band shell opens into the back of the stage but can be cut off by a curtain. See Fig. 9*k*.

Acoustically, the auditorium exemplifies as far as possible the ideal auditorium described in Chapter VII, namely, with stage conditions that reflect sound beneficially for the performers, and an auditorium for listening that is quite free from sound reflected from the walls and that approaches the deadness of outdoors. Thus, the band shell at the back of the stage is similar to the rectangular shape shown in Fig. 7*f*. It is lined with plaster on metal lath and has no sound absorbent except the clothing of the players and the large opening into the stage and auditorium. Professor P. S. Emrick, Director of the Band, writes:

> It has long been the conviction of the writer that a Band Shell should be a mixing bowl together with its purpose of directing the musical sounds to the ears of the audience. This idea has been incorporated in the Hall of Music at Purdue University in the design of the large Band Shell, which has produced results exceeding our expectations in that the blending of the various tone colors of the instruments gives a rich and velvety ensemble to a Symphonic Band.

The band music is not excessive in intensity in the auditorium, probably because it is moderated when passing through the absorbent stage, so that it reaches the audience much as it would in an outdoor theater. For performances on the main stage, a portable stage room was designed with splayed sides and sloping ceiling that will reflect sound to the performers so that they can hear themselves.

To approximate the second ideal of listening conditions in the auditorium, it was desirable to minimize reflections from the walls and to introduce considerable absorbing material. Focusing reflection from the rear wall on the main floor was avoided by making this surface in "stepped" plane sections instead of following the usual plan of having it curved to conform to the last row of seats. Sound absorption on this

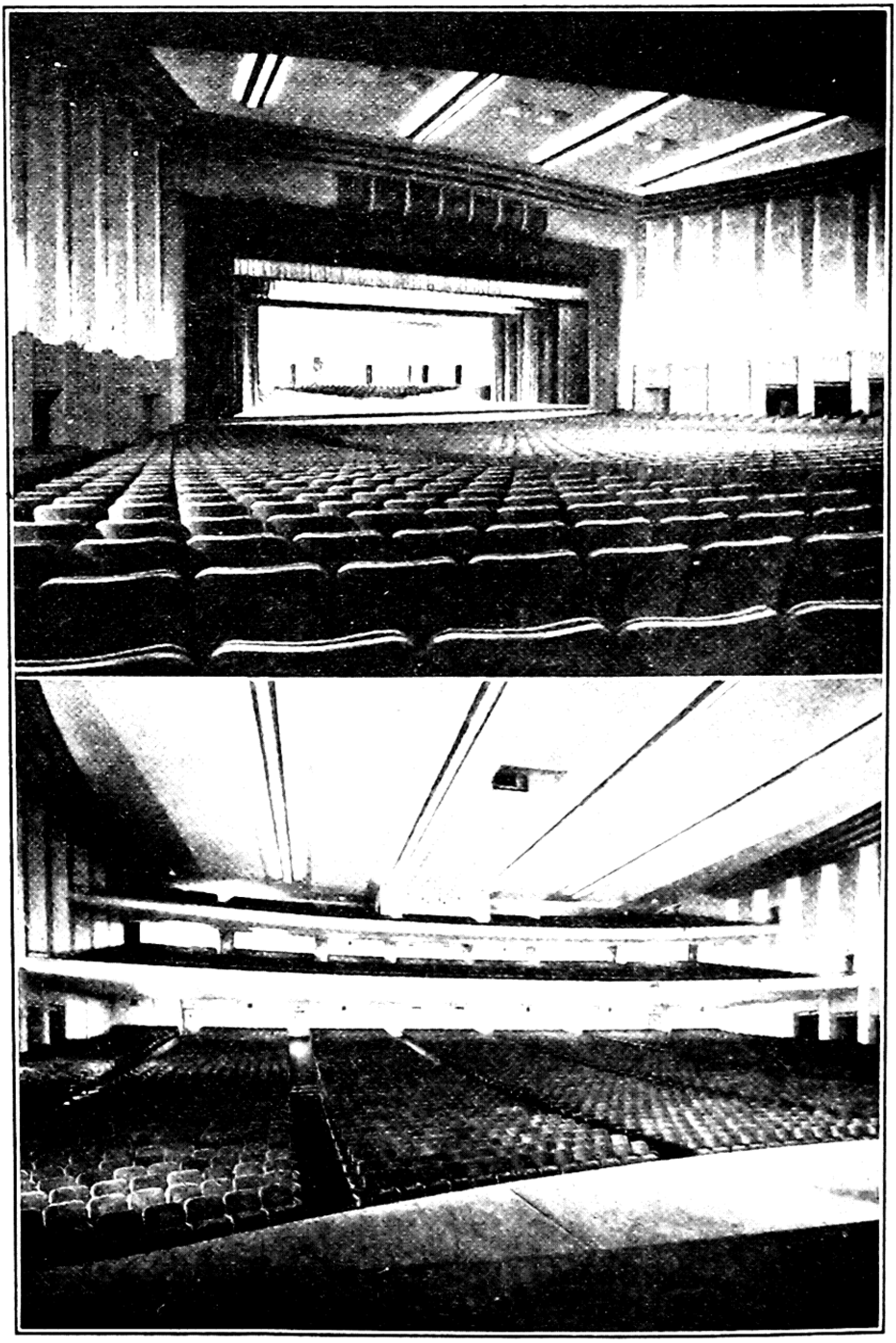

FIG. 9*k*. · Purdue Music Hall, specially designed for acoustics. (Walter Scholer, Architect.)

wall was provided by rock wool, 2 inches thick, backed with an air space, and faced with perforated Transite. The side walls and ceiling were treated with sound-absorbing material in panel form to absorb and break up reflection of sound. The side walls adjacent to the stage followed a gentle curve but were broken at the main floor level by openings into side passages, while the upper area was made zigzag with rather narrow sections of varying widths set at different angles, with panels of sound absorption placed on the sections facing the audience. Two balconies served further to break the reflecting expanse of the rear wall. The rear walls at the back of both balconies were covered with the same rock-wool construction as for the main floor wall, and the foyer at the back of the second balcony was heavily padded. Upholstered seats on the main floor and the two balconies, together with lined carpets on the aisles, completed the array of absorption needed.

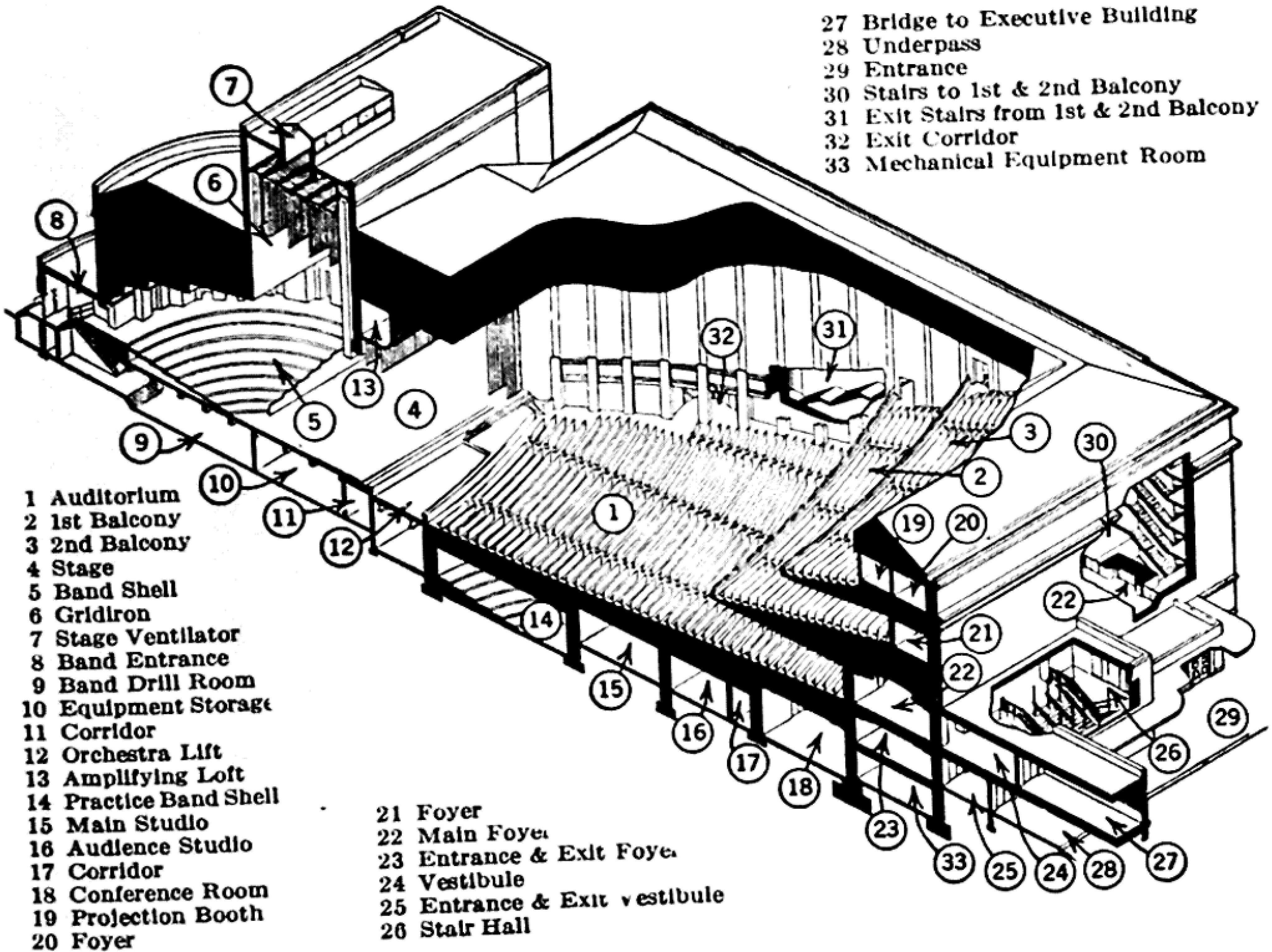

FIG. 9*l* (1). Isometric projection of the Purdue Music Hall.

The hall is equipped with an elaborate public-address system, but it has not been found necessary for musical numbers, either vocal or instrumental. Articulation tests in the empty room gave a satisfactory percentage of 85 per cent with the unaided voice and 87 per cent when

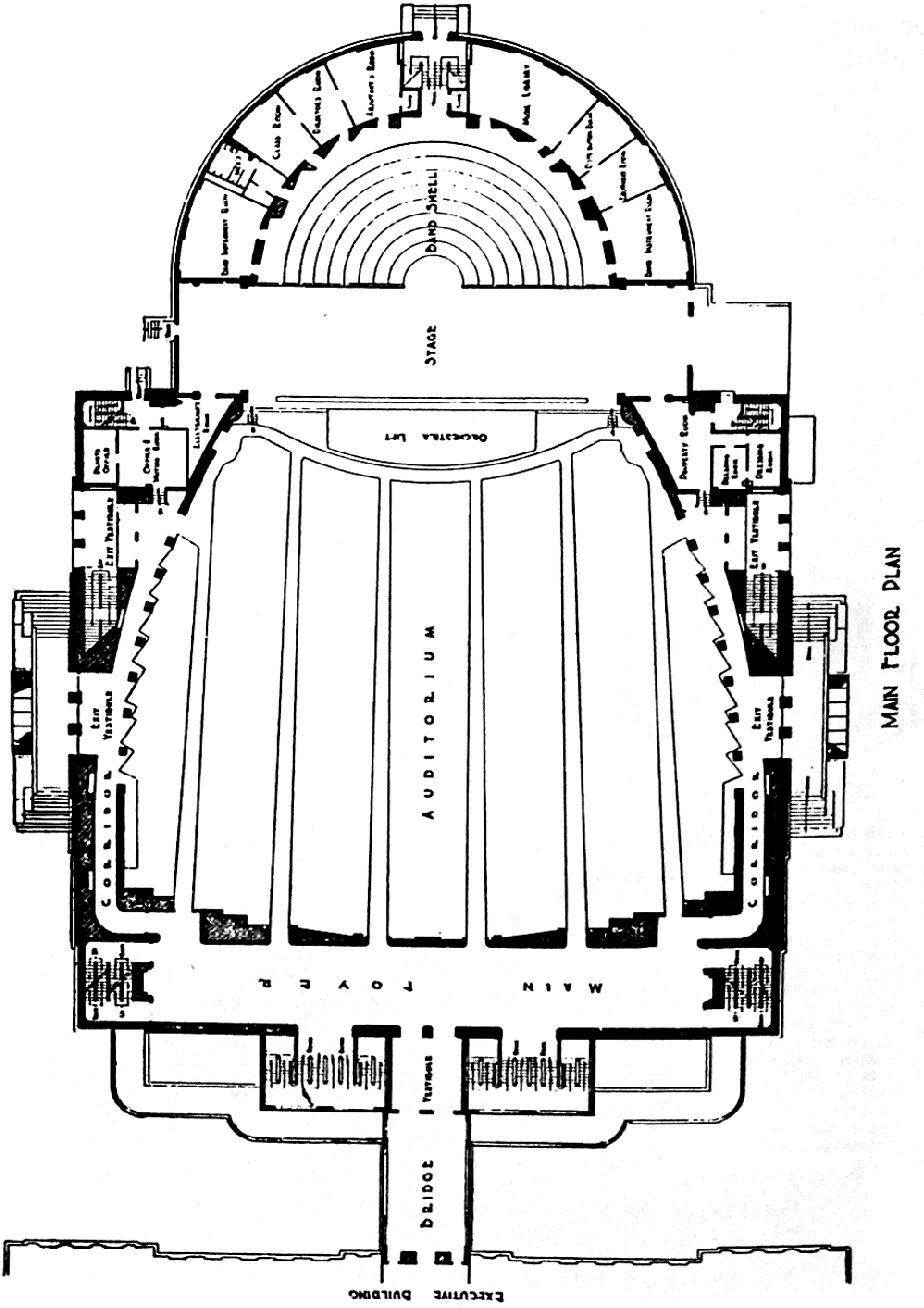

FIG. 9*l* (2). Plan of the Purdue Music Hall.

the public-address system was employed. For weak-voiced speakers and when an audience is present with the usual audience noise, the amplifying system has been found beneficial. Summing up, it appears that the ideal auditorium arrangements give the acoustic effects expected with their use, even for so large a room as the Purdue Music Hall, an achievement that is due in large part to the willingness of Mr. Scholer, the architect, to incorporate the recommendations for the acoustics in his design of the building.

Indianapolis Coliseum. This final example of acoustic design presented an unusual problem because of the large volume of 5,900,000 cubic feet. The Coliseum was designed to accommodate a variety of events — horse shows, ice hockey games, and other performances in the central arena, surrounded by the sloping tiers of seats for auditors; for conventions, orchestra concerts, and similar meetings when the central arena is used for the audience, in addition to the side seats. Two acoustic requirements were immediately apparent. First of all, a great amount of absorption was needed to control the reverberation, and a sound-amplifying system was necessary to make sounds loud enough to be heard easily. Figure 9*m* presents a view of the interior of the Coliseum.

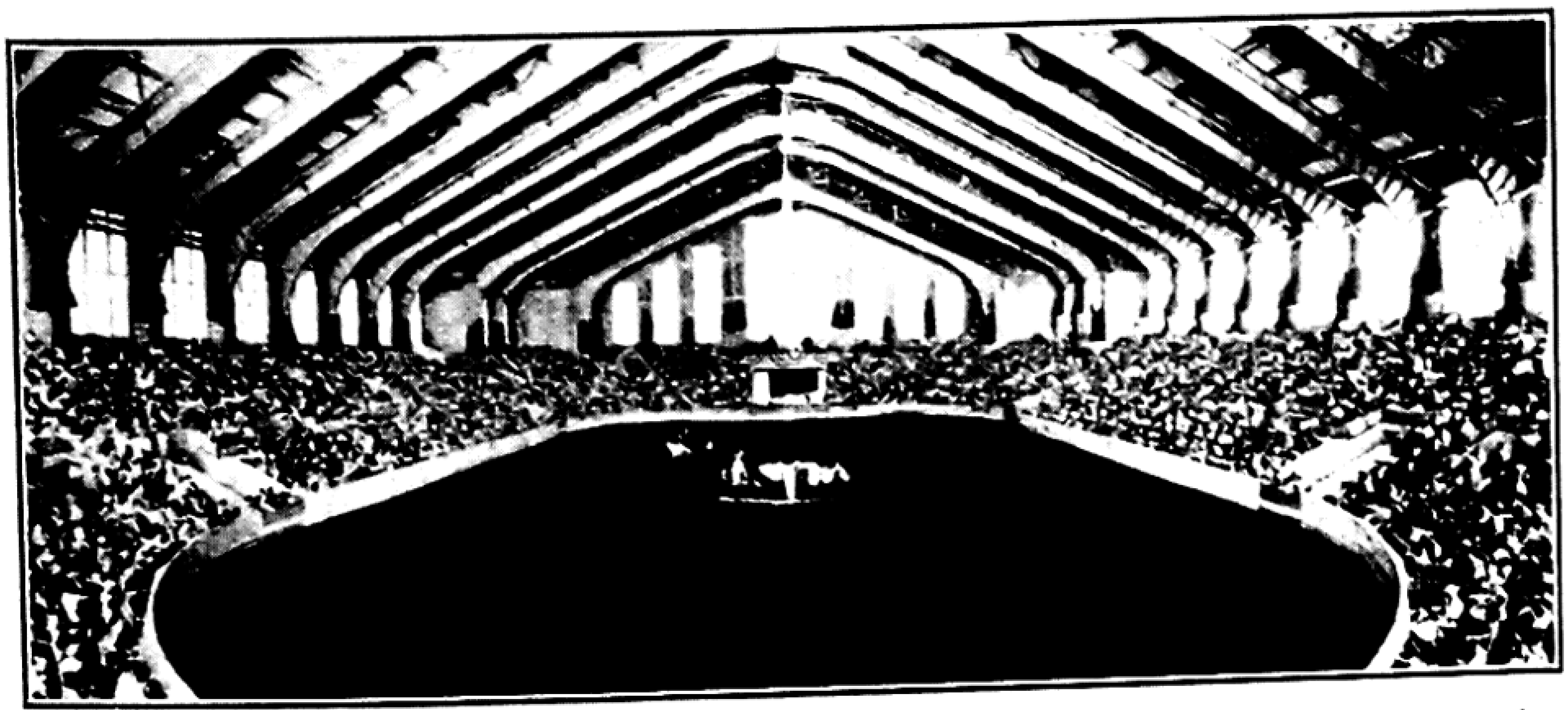

Fig. 9*m*. Indianapolis Coliseum. This very large auditorium required extensive sound-absorbing materials on the ceiling and walls to reduce the reverberation, and a public-address system to amplify the sounds of speaking and music. (Russ & Harrison, Architects. Photograph by J. C. Allen & Son.)

The problem of installing enough sound absorption was not so easy as in a smaller auditorium, because the ratio of the area for installation of material compared with the volume is smaller for the larger volume. It was therefore necessary to consider the application of material to all available surfaces. Accordingly, the entire under side of the ceiling was covered with Corkoustic of absorption coefficient of approximately 0.60. Instead of being attached to a completed ceiling, it was embedded in the concrete slabs as they were precast. The side walls, except for the large window areas, were constructed of sound-absorbing porous concrete blocks, which not only served as building units but also absorbed sound on both sides, the auditorium on one side and the hallways and offices on the other.

The amplification of sound was brought about by the installation of a powerful public-address system. The assembly of loud-speakers for the system was mounted on a " gondola " that was suspended from a central runway so that it could be raised, lowered, and moved to different locations along the center line of the room. This flexible arrangement allowed the system to be used for different events. For conventions, with audiences up to 25,000 people, the gondola could be placed over the speaker's platform so as to send amplified sound to all the seats in the room from the battery of loud-speaker horns that were directed effectively to cover all the seats. When the central arena was used for games of ice hockey, the gondola was located over the center of the room and the voice of the announcer could thus be amplified so as to be heard above the general noise level of the excited audience. For dances, phonograph music was fed through the amplifying system and adjusted in volume to give pleasing effects.

When empty, the room was too reverberant, but the conditions improved decidedly when the large audiences were present, owing to the absorption by the clothing worn.

CHAPTER X

HEARING AND SPEECH IN AUDITORIUMS

Purpose of an Auditorium. The purpose of an auditorium, as the name indicates, is to provide a room in which people can hear and understand, that is, where speaking and music are comfortably loud and intelligible. It is the intention in this chapter to discuss the conditions that affect the hearing of speech and music, including the distortion of sound caused by reflection from the surfaces of the room, by faulty loudness, and by excessive reverberation and noise.

Distortion by Reflected Sound. In the discussion of ideal auditoriums in Chapter VII, it was pointed out that most of the acoustic defects in a room were due to reflected sound, namely, reverberation, interference, resonance, echoes, and focal concentrations. Reflected sound concentrated by a concave wall is usually annoying to auditors because it mixes with the direct sound and produces a confusion for hearing. If the reflected sound arrives about $\frac{1}{15}$ second or more after the direct sound, an echo is heard. This defect has already been mentioned under the subject of reflection and was discussed in the acoustic design of rooms. It is thus sufficiently evident that the reflecting surfaces of rooms should be given special consideration both in regard to shape to reduce the concentrations and in the installation of materials to provide adequate absorption.

Blurring of Sound by Reflection. Sometimes the reflected sound combines with the direct sound so as to produce a blurring of speech and music. Consider the sound of the word *man*, as pictured in Fig. 10*a*, as it passes directly from the speaker to the auditor. The vowel *a* is bounded by the consonant *m* on one side and by *n* on the other, the total average time taken to say such a word being 0.3 second.[1] Now suppose the same word also to reach the auditor after reflection from a wall, so that it arrives 0.05 second later than the direct sound. The resultant of the direct and reflected sounds shows a beneficial reinforcement. The consonants are lengthened somewhat and the vowel is intensified, but it is still the word *man*.

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[1] I. B. Crandall, "The Sounds of Speech," *Bell Telephone Laboratories Reprint* B-162–1, p. 23, 1925.

If, however, the reflected sound comes 0.1 second after the direct sound, a blurring is set up as pictured in Fig. 10*b*.[2] The difference in path between the direct and reflected sounds is readily calculated. Sound travels about 1,120 feet per second at ordinary temperature, so that in 0.05 second it will travel 56 feet (0.05 × 1,120 = 56). This means that the reflecting wall near a speaker must not be farther away than about 28 feet if blurring of words by the reflected sound is to be avoided. Petzold found a similar blurring effect for music, but with a shorter time of 0.035 to 0.042 second between the direct and reflected sounds, depending on the nature of the music, giving path differences of 39.2 and 47 feet respectively.

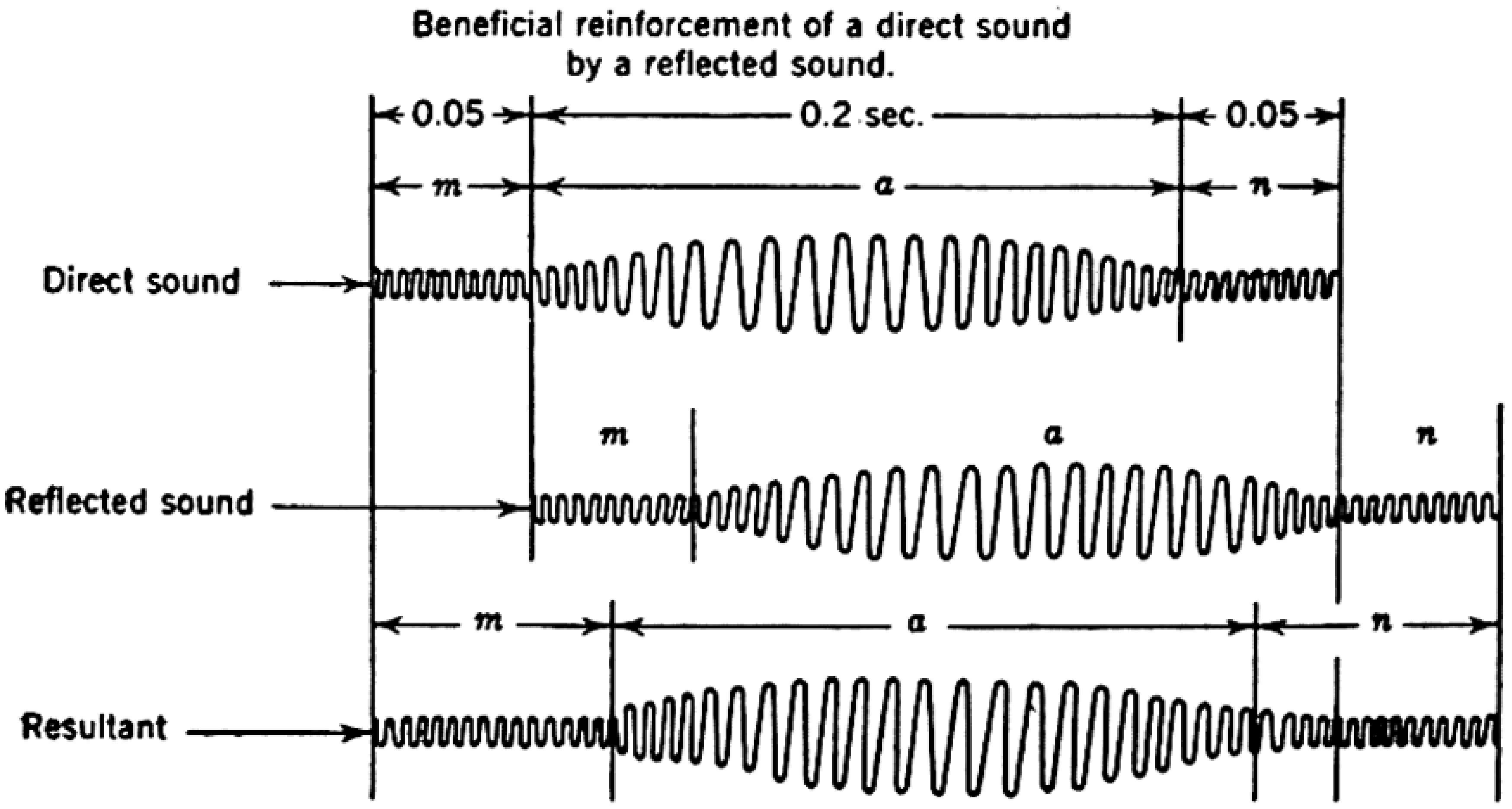
Beneficial reinforcement of a direct sound by a reflected sound.
0.05
0.2 sec.
0.05
m
a
n
Direct sound
m
a
n
Reflected sound
m
a
n
Resultant

FIG. 10*a*. Diagram showing how the spoken word *man* is beneficially reinforced by reflected sound.

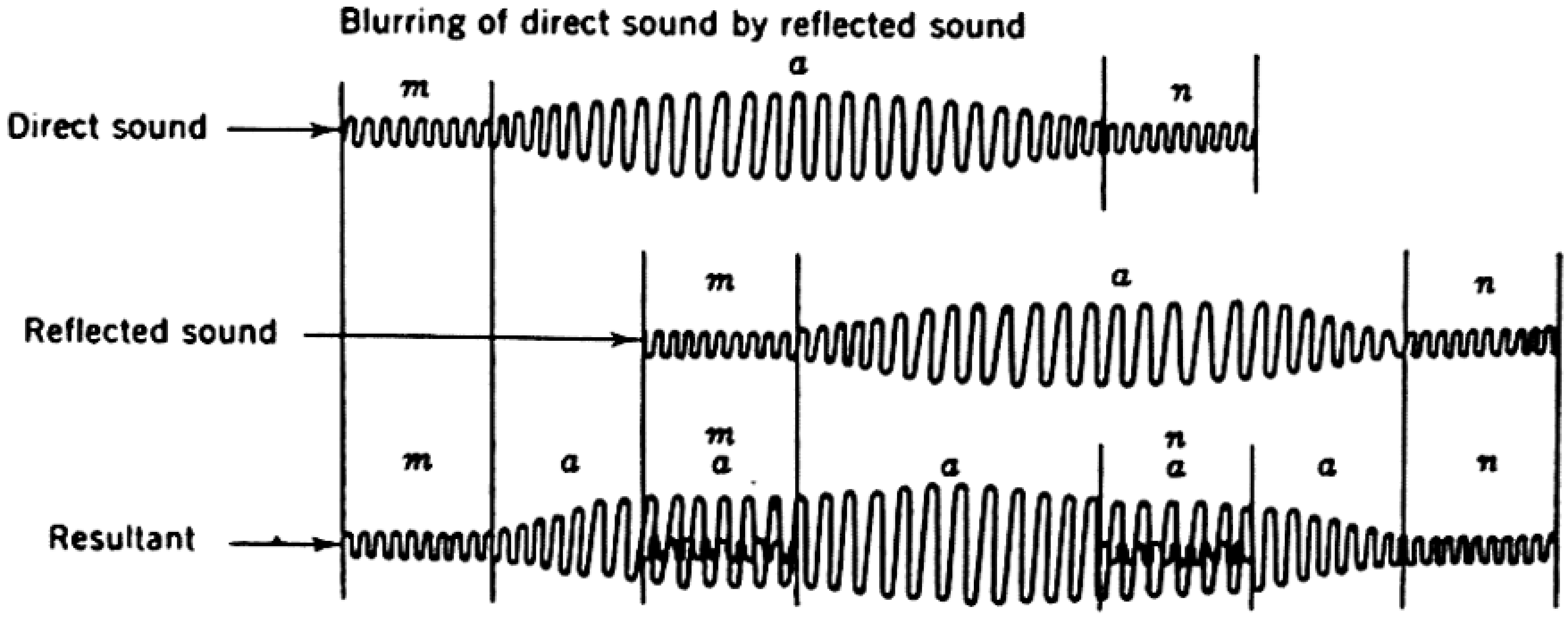

FIG. 10*b*. Diagram showing how the spoken work *man* is blurred by reflected sound.

This conclusion of Petzold's indicates the importance of studying the reflecting surfaces near speakers and musicians to avoid blurring effects.

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[2] E. Petzold, *Elementare Raum Akustik,* p. 8.

Usually in auditoriums, the space about the performer has been decided by other requirements than acoustics. The large stage house of the modern theater gives little practical opportunity for suitable reflecting walls. In smaller auditoriums, it would be easier to design such reflectors, without the usual heavy absorbing curtains.

Such reflecting surfaces should preferably be plane, and situated not more than about 20 feet from the performer — a smaller distance would give better results — and inclined so as to reflect sound to the audience. Under these circumstances, the direct sound from the performer is reenforced without distortion by a number of images, all giving the same sound simultaneously.

Not only are the auditors benefited by this arrangement, but the performer himself gets an immediate response to his effort that allows him to adjust his speech or music to get the best effect. Without this, the performer feels lost, and the resulting sound, particularly music, lacks perfection. Musicians state that they prefer to sing or play near a wall, and always with a resonant stage floor, without carpet, presumably because of the reassuring vibrations given by such reflecting surfaces.

Articulation. The measurement of the recognition of speech sounds, called articulation, has been studied extensively by Fletcher and his associates at the Bell Telephone Laboratories.[1] Originally, " articulation tests " were devised to test speech transmission over telephone lines. The " percentage articulation " indicates the percentage of typical speech sounds that can be heard correctly when transmitted over the telephone. These tests have been adapted by Knudsen for testing the articulation in auditoriums.[2] The experimental procedure is described in Chapter XI. After considering the various factors that affect the articulation, Knudsen set up an equation to express the percentage of articulation, P:

$$P = 96\, k_l\, k_r\, k_n\, k_s$$

k_l is the reduction factor due to inadequate loudness.
k_r is the reduction factor due to excessive reverberation.
k_n is the reduction factor due to extraneous noise.
k_s is the reduction factor due to shape of the room.

First of all, Knudsen conducted an experiment outdoors (no reverberation), under quiet conditions (no noise), when the observers were near the speaker (adequate loudness). Under these favorable circumstances, all the k's were assumed to be equal to unity, but the articulation test showed that the percentage was not 100, but 96, thus indicating that perfect hearing is not to be expected under any usual conditions. Speakers do not always enunciate distinctly, and observers do not always hear correctly.

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[1] *Speech and Hearing*, Chapter 3.

[2] *Jour. Acous. Soc. Amer.*, Vol. 1, p. 56, 1929.

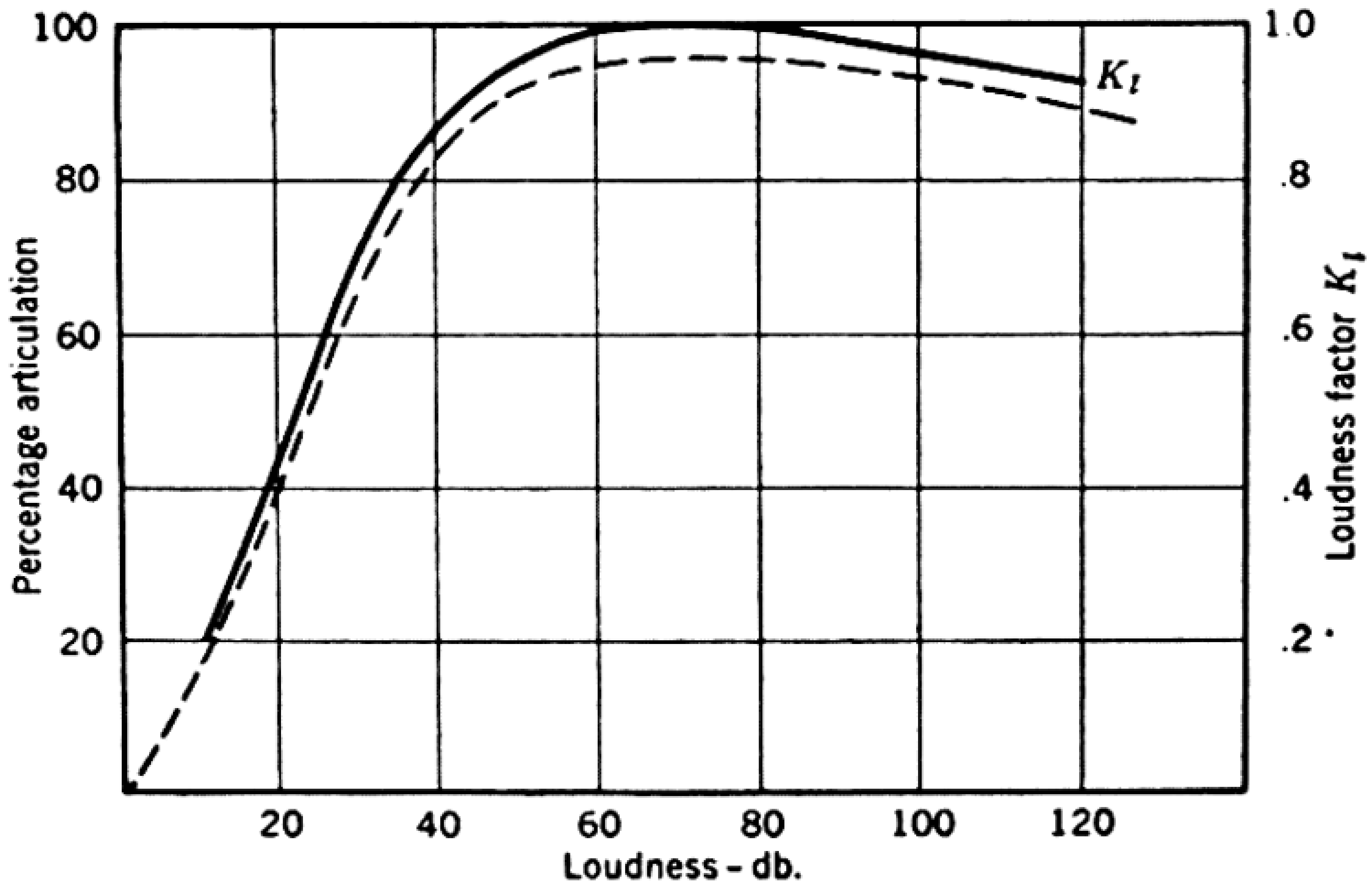

FIG. 10c. Curve showing the effect of loudness of spoken words on the perception of speech, taken from Fletcher's data. The dotted line gives the percentage articulation for different loudness levels. The solid line gives the corresponding loudness reduction factor, k_l, according to Knudsen.

Reduction Due to Loudness. Figure 10c shows results on loudness (dotted line) obtained by Fletcher. Maximum intelligibility of speech is reached when the loudness is about 70 db. Between 70 and 100 db, the intelligibility is still good, but from 0 db to about 30 db the intelligibility is unsatisfactory. To get values for the factor k_l, Knudsen assumed 100 per cent articulation for the 70-db sound, for which $k_l = 1$, with proportionate changes for the other values (solid line in Fig. 10c).

In this connection, Knudsen measured the decibel level of sound of speakers' voices in a small auditorium of 27,000-cubic-foot volume, and found that the level fell considerably short of the desired 70-db optimum observed by Fletcher. In the small auditorium, the average level for six speakers was 50.7 db, and for eight speakers in the large auditorium, the average was 45.7 db. He concluded that in large auditoriums it is impossible for an ordinary speaker to maintain a satisfactory intensity level without the aid of amplifiers.

Reduction Due to Reverberation. The articulation was tested in a number of auditoriums with different times of reverberation. On the basis of these tests, Knudsen constructed the curve shown in Fig. 10d, which gives the values of k_r for different reverberation times, when the loudness is adjusted for 70-db sound level. For times of reverberation of 0.5 second and less, the value of k_r is taken as unity, indicating that the intelligibility of speech is 100 per cent if the reverberation is very small. For times greater than 0.5 second, the articulation decreases about 6 per cent for each second increase in the reverberation time.

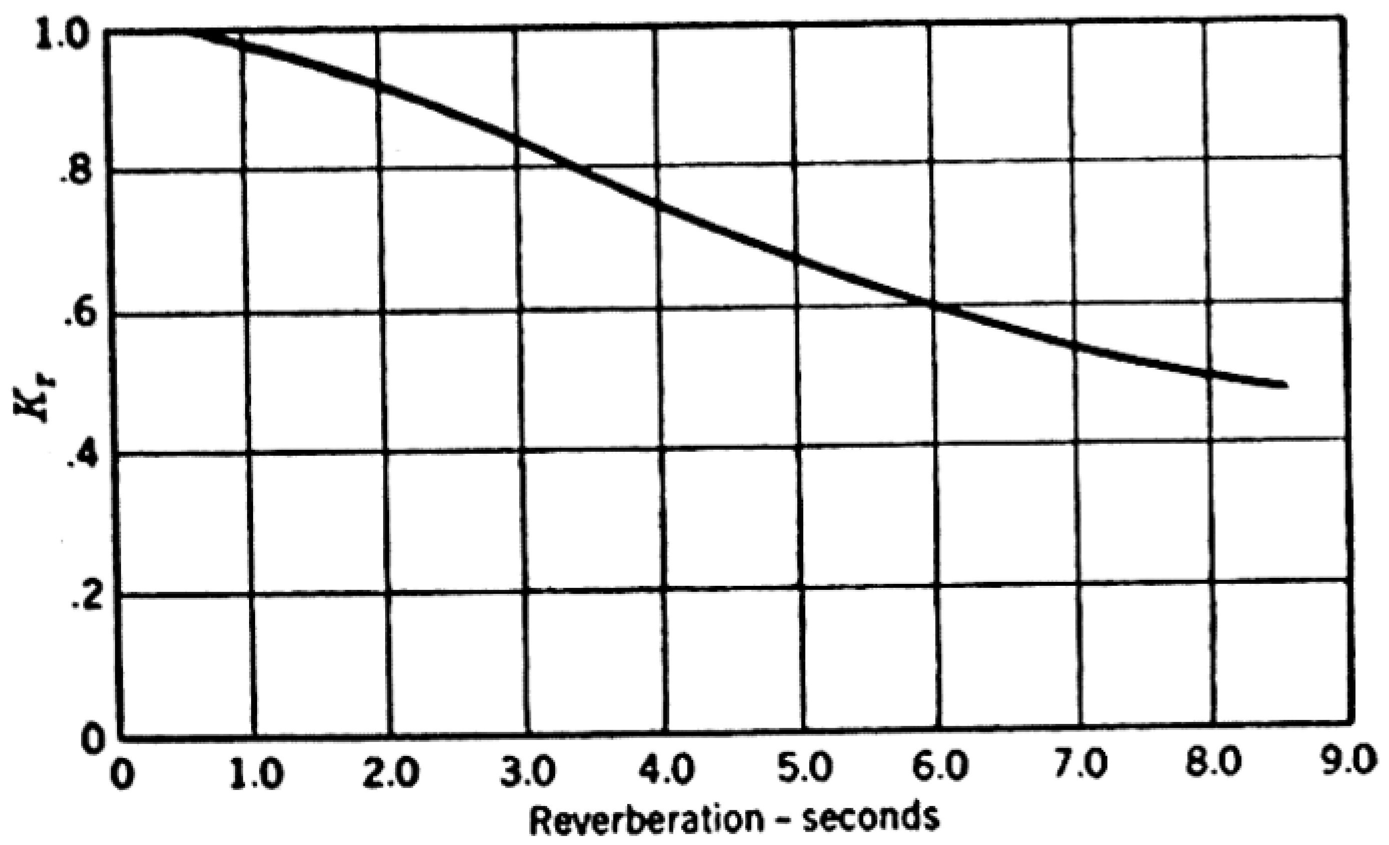

FIG. 10*d*. Graph giving the reverberation reduction factor, k_r, for different times of reverberation. (Knudsen.)

Reduction Due to Noise. A preliminary experiment was performed in which a controlled interfering noise was set up by telephone receivers placed about 1 inch from the observer's ears. It was found that an ordinary noise was worse for intelligibility than pure tones, because a noise includes many frequencies. The data thus obtained were used

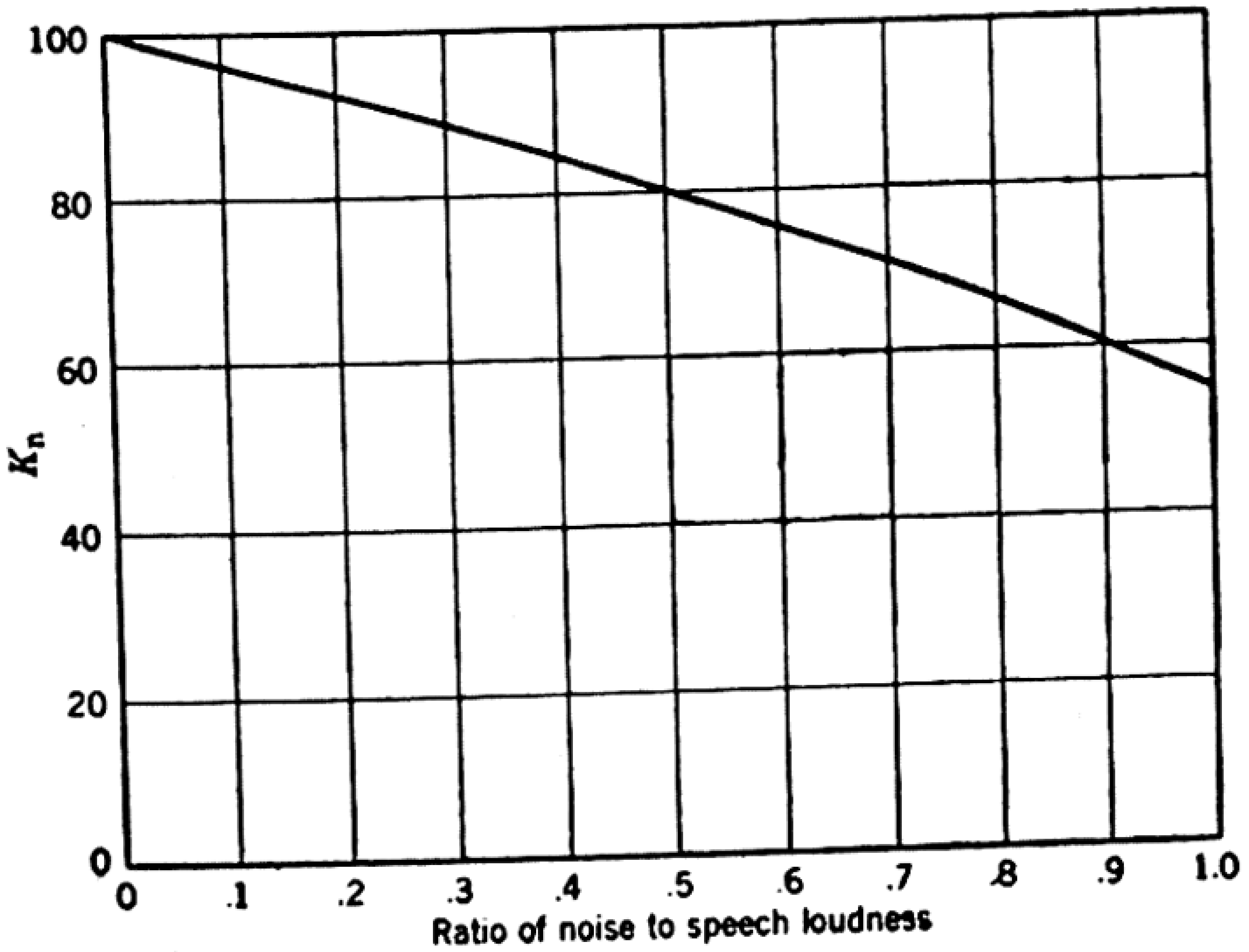

FIG. 10*e*. Graph showing how the noise-reduction factor, k_n, depends on the loudness of noise. The abscissas give the ratio of noise loudness to speech loudness, both being expressed in decibels.

in setting up the curve of Fig. 10*e*, which gives the articulation compared with the ratio of noise to speech level. For example, if the noise is zero, the articulation is 100 per cent; if the noise is 0.5 as intense as the speech, the articulation is reduced to 80 per cent.

Reduction Due to Shape of the Room. It is difficult to express this factor in a graph. Curved walls produce strong concentrations and echoes, with resultant loss of intelligibility. It is obviously necessary to modify shapes of surfaces in rooms that produce unequal distribution of sound.

Summary. The combined effect of all the factors may be estimated by inspection of the graphs and by calculation in the general equation. For example, if the loudness of sound in a particular room is 40 db for which k_l is 0.90, with a reverberation time of 3.5 seconds giving k_r a value of 0.8, with the noise level 0.5 as great as the speech level for which k_n is 0.8, and with the shape of the room properly adjusted to give k_s equal to 1, the resultant percentage articulation is calculated to be:

$$P = 96 \times 0.9 \times 0.8 \times 0.8 \times 1 = 55\%$$

CHAPTER XI

ACOUSTIC FIELD TESTS

Purpose of Tests. " Field tests " in auditoriums are conducted to ascertain the degree to which the acoustic conditions will give acceptable hearing of speech and music. These tests involve measurements by instruments and by personal observation of the articulation, time of reverberation, loudness, distribution of sound, and the performance of sound systems. For reliable results, the services of an acoustical engineer are required who is familiar with the operation of the instruments used and the theory underlying the acoustical measurements. Such tests are necessary for auditoriums in which it is planned to exhibit sound motion pictures so that suitable adjustments of the acoustic conditions can be made, if necessary; also, in some cases, these tests are made for the approval of acoustic specifications. A description of the tests follows, with comments on the conditions.

Articulation. One of the simplest tests made is a measure of the articulation, which tests the intelligibility of speech. A speaker on the stage recites a list of specially selected words, while observers in different positions in the room write down what they think they hear. This instructive procedure was developed at the Bell Telephone Laboratories, as described later in this chapter. A sound-amplifying system usually improves the articulation. For satisfactory speaking the correct interpretation of words should not be less than 80 per cent.

Time of Reverberation. One of the principal conditions in awarding a contract for the installation of sound-absorbing materials in an auditorium is that the time of reverberation in the finished room shall have a specified value in the region of a stated frequency with a reasonable tolerance of perhaps 5 per cent, for example, 1.75 ± 0.05 seconds at 512 cycles per second. For some rooms, these times are specified for three frequencies, 128, 512, and 2,048 cycles per second, as indicated for the optimal values discussed in Chapter VI.

The time of reverberation in an auditorium may be determined by a high-speed level recorder, an instrument that records graphically the time rate of decay of the sound in decibels. Figure 11*a* shows such a graph. Owing to certain resonances and interferences in the room, the sound dies away unevenly, but repeated measurements on the same waxed paper give overlapping graphs that show the average. Figure 11*b* shows some of the results obtained by means of the graphs. For large rooms or for high frequencies, the decay is smoother. The use of a "warble tone" as the source of sound is common in experimental work to reduce the fluctuations due to resonances and standing waves. A warble tone is the resultant effect obtained when a sound source is varied regularly approximately 10 per cent above and below its mid-frequency, e.g., 500 ± 50 cycles per second.

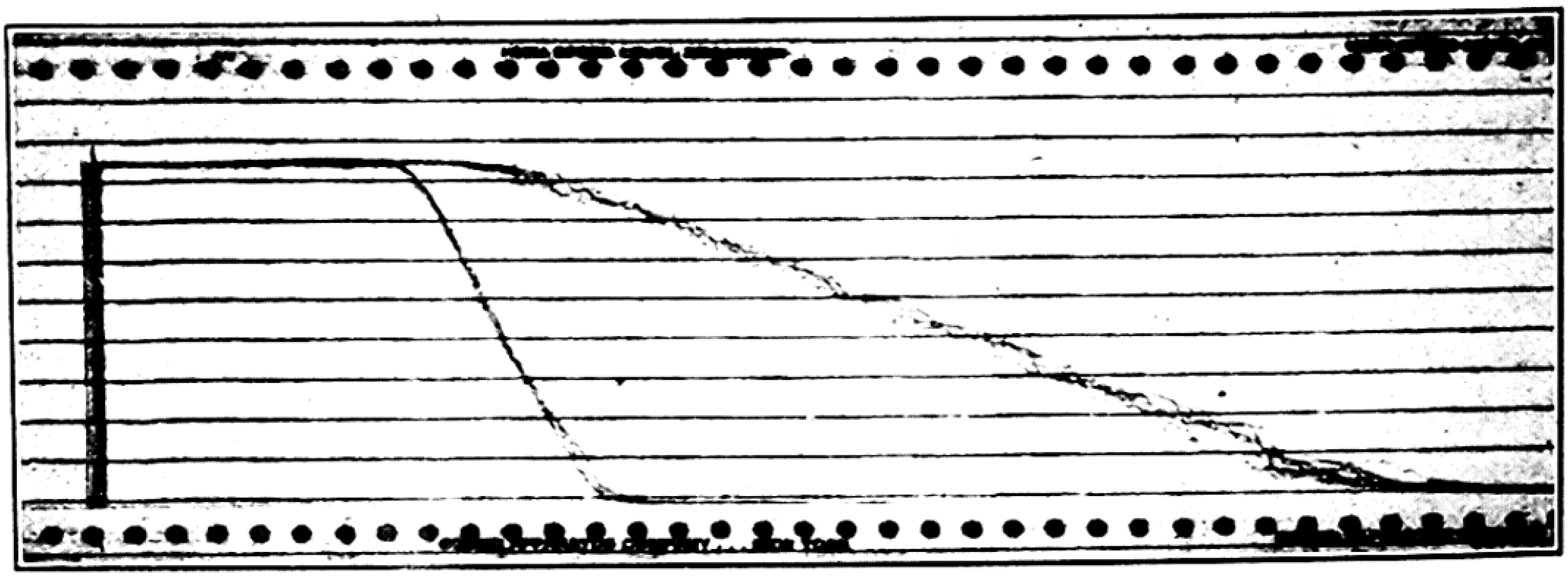

FIG. 11*a*. Photograph of waxed paper showing tracings of instruments in recording the decay of sound in a room. Repeated measurements give overlapping tracings that allow the average trace to be obtained easily. (Beranek.)

Loudness. Measurement of loudness requires the use of instruments, since any estimation by the ear is untrustworthy. A sound-level meter measures the intensity of sound in decibels, from which the loudness may be found, if desired. This instrument should be of a type that gives readings comparable with what the ear hears, as well as the actual intensity. For example, in testing an auditorium, a ventilation noise was barely perceptible to the ear and was not annoying. When this noise was measured by the sound-level meter, the ear network read 35 db, which agreed with the personal impression, but the actual level in physical units was 60 db. The ear measurement thus gave the most useful information, since the purpose of the field tests is to ascertain how satisfactory the room is for auditors.

Measurements should be taken for the noise level in the room when no performance is in progress. If this background of noise is more than about 40 db, it will be annoying to an audience, and the source of the disturbance should be investigated and the noise reduced. Such sources are usually found in the ventilation system, talking in lobbies, street traffic, etc.

Measurements should be taken also for the sound level of speaking and music, which should be 50 db or more for satisfactory hearing. For large auditoriums, a sound-amplifying system is necessary to give suitable loudness in all parts of the audience area.

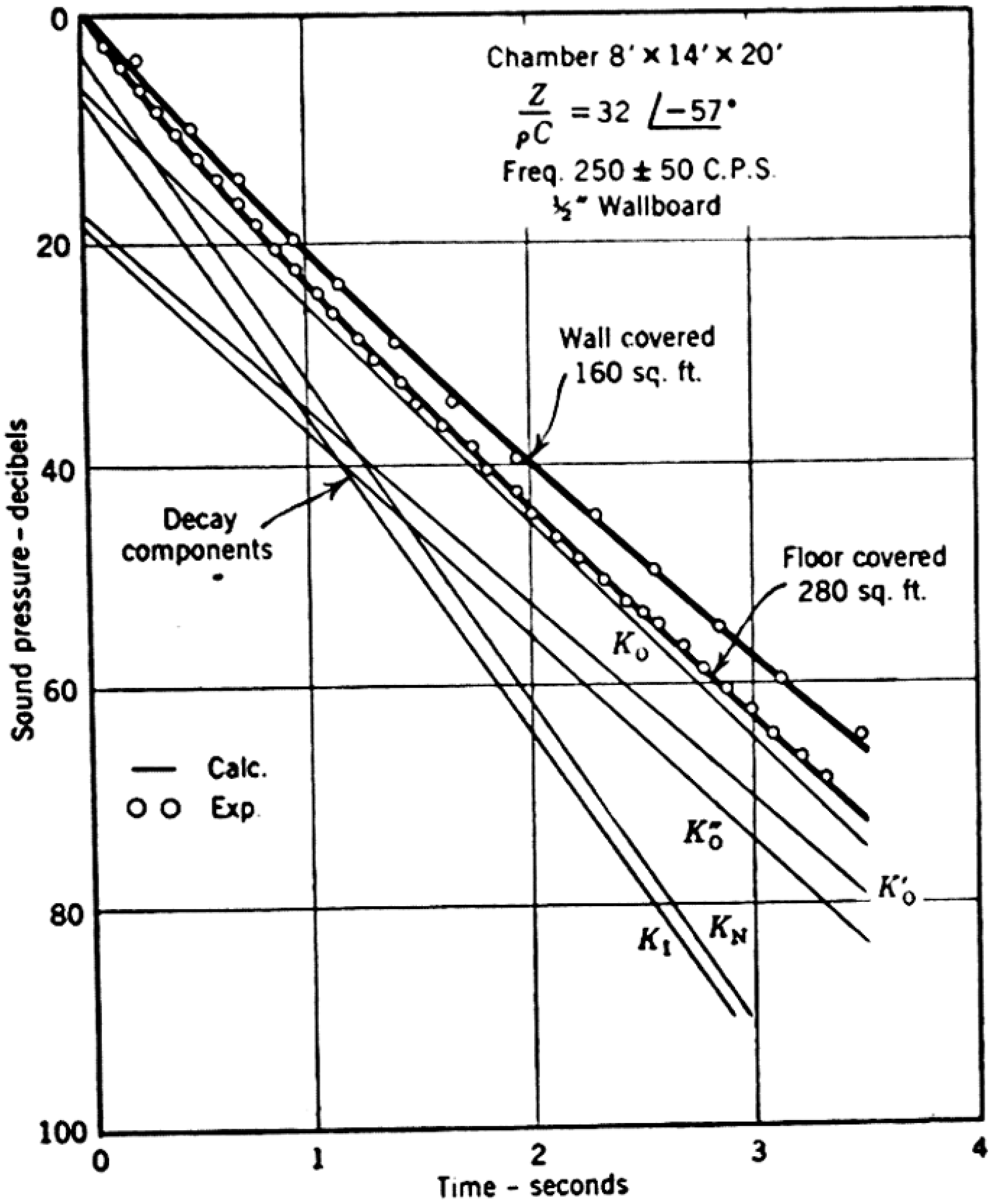

FIG. 11*b*. Graphs showing data for acoustic values of absorbing materials, obtained by use of tracings as shown in Fig. 11*a*. (L. Beranek, *Acous. Jour. Amer.*, Vol. 12, p. 14, 1940.)

Distribution of Sound. It is obviously important to get fairly uniform sound levels in different locations in an auditorium, a condition that may be expected if the shape of the walls and a suitable source of sound are coordinated, as explained in the chapter on the acoustic design of auditoriums. A loud-speaker has an advantage over the unaided voice in directing sound more uniformly to the audience. When more than one loud-speaker is needed for a room, a more uniform distribution of sound intensity is obtained if the speakers are placed near together. The sounds from two speakers separated by some distance will interfere, depending on the frequency of the sounds, thus producing an unevenness in the distribution in the room. Some of these effects can be observed by the ear, but it is usually more satisfactory to measure the distribution with a sound-level meter.

Articulation Tests. One of the most direct, most interesting, and most instructive tests of the acoustics of a room is the articulation test, which was devised to give an estimation of the intelligibility of speech. Though the results obtained are not very accurate unless the observers have had at least a month's experience in the tests, yet a fairly good estimate of the room acoustics can be found with inexperienced observers. The experimental procedure is as follows. A speaker on the platform of an auditorium reads sentences, each containing three test words, while observers in different parts of the room write down what they think they hear. The observations are then corrected, any words heard incorrectly being noted, and the percentage of correct interpretations is recorded. Two lists of well-known words, Table 11*a*, have been carefully selected for these tests that give vowels and consonants in common use in the English language.[1] Note that the *vowel* words all begin with the consonant *b* and end with either *t* or *k*; also, note that the *consonant* words all have the same vowel sound, long *i* or short *i*, an arrangement that allows the observer to concentrate his attention on the particular sound under test, and also requires him to recognize the test sound in order to understand the word.

Table 11*b* gives a list of sentences with test words inserted that are similar to those in Table 11*a*. Note that the vowel (or consonant) to be tested is written in capital letters.[2] The first test word in each sentence contains a vowel, and the last two words have consonants to be tested. Before making up the sentences, the vowel and consonant words are written on separate cards. The vowel cards are kept together and shuffled, the same procedure being followed with the consonant cards, so that a new combination of words can be obtained for each successive test.

Experimental Procedure. Observers are asked to take a few minutes to familiarize themselves with the words to be tested, after which they are given several preliminary tests for practice before the final test is made. In Table 11*b*, used only by the caller, it is to be noted that each sentence starts with a phrase such as, " The first is." This introductory phrase prepares the observers for the test words that are to follow; also, it introduces any reverberation effect. Table 11*c* is a sample data sheet (Articulation Test Record) with the words written in by one of the observers, where *V* and *C* are the numbers of correct interpretations

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[1] H. Fletcher and J. C. Steinberg, " Articulation Testing Methods," *Bell System Tech. Jour.*, October, 1929; also, *Jour. Acous. Soc. Amer.*, supplement to January, 1930.

[2] N. A. Watson and V. O. Knudsen, " Selective Amplification in Hearing Aids," *Jour. Acous. Soc. Amer.*, Vol. 11, 406, 1940.

TABLE 11*a*

LISTS OF WORDS USED IN ARTICULATION TESTS (Fletcher-Steinberg)

VOWEL WORD LIST (ENGLISH WORDS)

Sound to be Graded	*English Words in the List*	
a'	bat	back
ā	bait	bake
e	bet	beck
ē	beat	beak
i	bit	bit
ī	bite	bike
o	but	buck
o'	bought	balk
ō	boat	boat
u	book	book
ū	boot	boot

CONSONANT WORD LIST (ENGLISH WORDS)

Sound to be Graded	*English Words in the List*	
b	by	by
ch	which	which
d	die	die
f	fie	whiff
g	guy	wig
h	high	high
j		
k	wick	wick
l	lie	will
m	my	whim
n	nigh	win
ng	wing	wing
p	pie	whip
r	wry	wry
s	sigh	sigh
sh	shy	wish
th'	thy	with
th	thigh	thigh
t	tie	wit
v	vie	vie
w	why	why
y		
z	whiz	whiz
st	sty	whist

Note: The *h* following *w* is not pronounced in such words as whim, whip, etc.

TABLE 11*b*

Articulation Test Record

*Date*____________________ *Articulation* V___C___S___

Test No. ____________________ *Observer* ____________________

*List No.*____________________ *Caller*____________________

Conditions of Test ____

No.		Called		Called		Called	
1	The first is	bAIt		Set		Ret	
2	Now try	bUt		riP		Ben	
3	Next comes	bOAt		STy		riFF	
4	Group 4 is	bAke		Guy		wiN	
5	The next is	bAlk		Jen		THigh	
6	Now comes	bAt		Pen		Yen	
7	Listen to	bIte		riM		Let	
8	Try to hear	bEt		Men		riNG	
9	Next comes	bOUght		Tie		THy	
10	Group 10 is	bOOk		riCK		wiNG	
11	Please try	bIt		SHy		wiCK	
12	Can you hear	bOUt		WRy		Jet	
13	Now try	bEAt		High		Yet	
14	The next is	bOOt		Net		Wen	
15	Listen to	bEck		Vet		wiLL	
16	Try to hear	bOOT		Hen		Sigh	
17	The next is	bOOk		Fen		riG	
18	Now comes	bIke		whiZ		Pet	
19	Now try	bAck		THen		riD	
20	Group 20 is	bIt		riCH		wiTH	
21	Listen to	bOUt		riB		Ten	
22	Try to hear	bEAk		Fie		wiSH	
23	Can you hear	bUck		WHiz		whiST	
24	Next comes	bOAt		whiCH		Den	
25	The last is	bArk		Vie		Wet	

TABLE 11c

ARTICULATION TEST RECORD

Date____________________ *Articulation* V24 C45 S78
Test No. ____________________ *Observer*____________________
*List No.*____________________ *Caller*____________________
Conditions of Test ____________________

No.			Incorrect		Incorrect		Incorrect
1	The first is	bait		set		ret	
2	Now try	but		rip		ben	
3	Next comes	boat		sty		rip	X
4	Group 4 is	bake		buy	X	win	
5	The next is	balk		jen		thigh	
6	Now comes	bat		pen		yen	
7	Listen to	bite		rim		let	
8	Try to hear	beet	X	men		ring	
9	Next comes	bought		tie		thy	
10	Group 10 is	book		rit	X	wing	
11	Please try	bit		shy		wick	
12	Can you hear	bout		wry		jet	
13	Now try	beat		high		yet	
14	The next is	boot		net		when	X
15	Listen to	beck		vet		will	
16	Try to hear	boot		hen		sigh	
17	The next is	book		fen		rig	
18	Now comes	bike		whiz		pet	
19	Now try	back		hen	X	rid	
20	Group 20 is	bit		rich		with	
21	Listen to	bout		rib		ten	
22	Try to hear	beak		fie		wish	
23	Can you hear	buck		whiz		whist	
24	Next comes	boat		which		den	
25	The last is	bark		vie		wet	

of vowels and consonants respectively. After a test, this data sheet is compared with the words given in Table 11*b* and the incorrect interpretations are noted. The value of vc^2 is then calculated for insertion in the Fletcher-Steinberg equation:

$$\frac{S}{100} = 1 - (1 - vc^2)^{0.9}$$

in which S is the percentage articulation, v is the fraction of vowel words correctly interpreted, and c is the fraction of correct consonant words. For example, if one of the vowel words in the list of 25 in Table 11*b* is heard incorrectly, then v is 24/25, or 0.96; if 5 consonants are heard incorrectly out of the total of 50 in the list, c is 45/50, or 0.90. The value of vc^2 is thus 0.96 × 0.90 × 0.90, or 0.78. When the accuracy of the observations warrants it, this value of vc^2 can be substituted in the equation to get S, but usually the difference between $S/100$ and vc^2 with inexperienced observers is greater than experimental error, and the value of 100 times vc^2 may be taken to express the percentage articulation. When greater accuracy is sought, Table 11*d* may be used to save the calculation in the use of the above equation.

TABLE 11*d*

Value of vc^2	Corresponding value of S, found by subtracting the following from vc^2
0.00–0.05	0.00
0.06–0.16	0.01
0.17–0.29	0.02
0.30–0.47	0.03
0.48–0.79	0.04
0.80–0.90	0.03
0.91–0.95	0.02
0.96–0.99	0.01
1.00	0.00

As an example, suppose the value of vc^2 is found to be 0.35, which lies between the values of 0.30 and 0.47; then the corresponding value of S is $(0.35 - 0.03)\ 100 = 32$. These articulation tests are being used extensively for observations with hard-of-hearing people, and improved methods of conducting the experiments are being developed.

The interpretation of these tests, according to Knudsen, who adapted them for measuring auditorium acoustics, is as follows:[1]

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[1] *Architectural Acoustics*, p. 344.

A large series of tests seems to warrant the following conclusions:

(1) If the articulation be 85 per cent or more, the hearing condition will be very good.

(2) If the articulation be 75 per cent, the hearing condition will be satisfactory, but attentive listening is required.

(3) If the articulation be 65 per cent, the hearing condition is just barely acceptable, but the listening is very fatiguing.

(4) If the articulation be less than 65 per cent, the hearing condition is unsatisfactory.

In applying these conclusions of Knudsen's, it is assumed that the room has acceptable values of loudness, reverberation, extraneous noise, and no focal concentrations of sound. If the room is faulty in these respects, corrections to get acceptable conditions can be made according to the curves given in Chapter X, "Hearing and Speech in Auditoriums." For auditoriums in which the acoustic conditions are very faulty, Fletcher and Steinberg recommend the use of an intelligibility list which gives a series of discrete sentences that are more easily understood than the test words.[1] The value of the articulation S is then

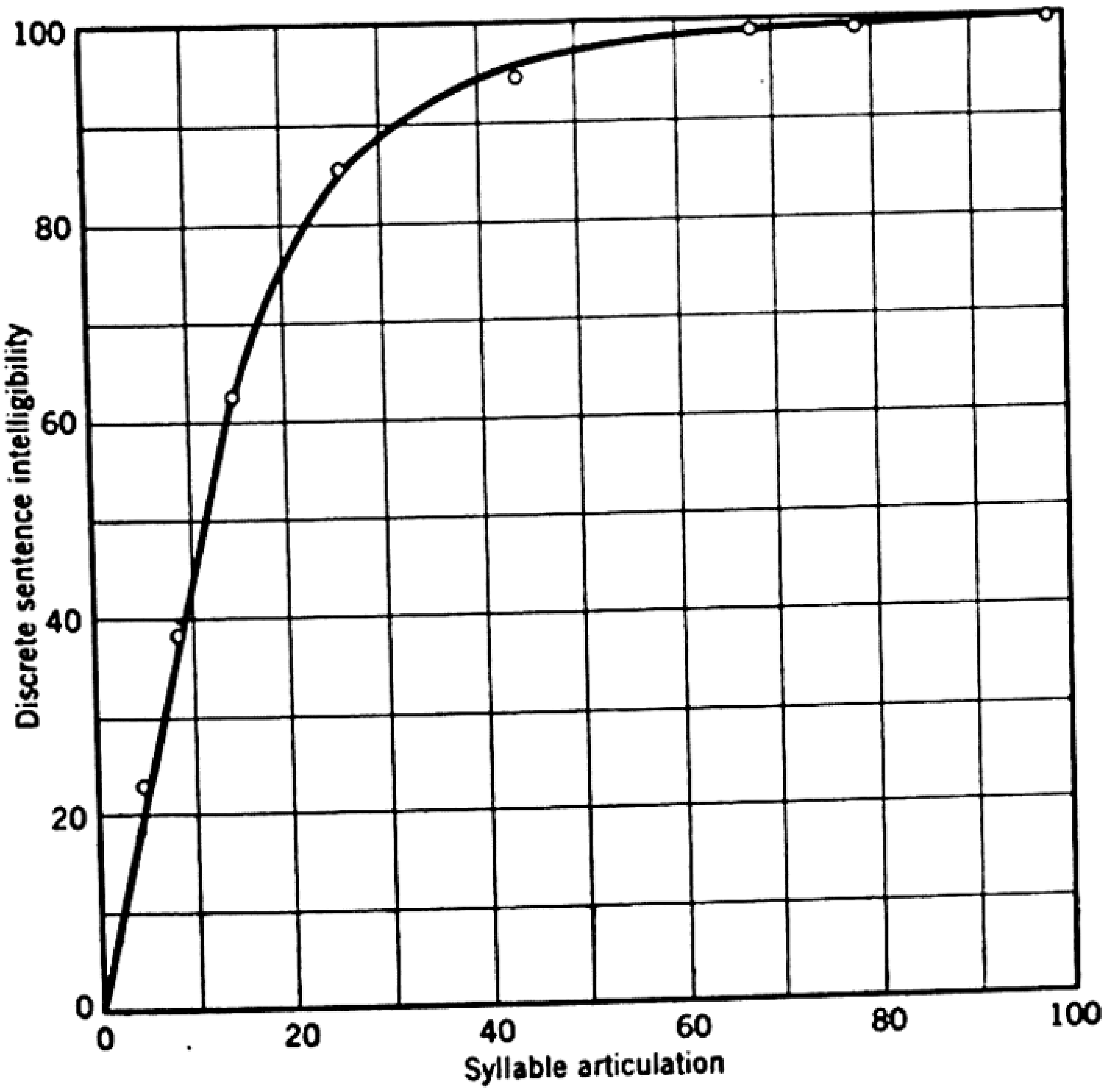

FIG. 11c. Graph for obtaining the percentage articulation from data on the understanding of spoken discrete sentences. (Fletcher and Steinberg.)

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[1] "Articulation Testing Methods," H. Fletcher and J. C. Steinberg, *Supplement to Jour. Acous. Soc. Amer.*, January, 1930; Also, *Bell System Tech. Jour.*, October, 1929.

TABLE 11*e*

INTELLIGIBILITY LIST (Fletcher and Steinberg)

1. Name a prominent millionaire of the country.
2. How large is the sun compared with the earth?
3. Why are flagpoles surmounted by lightning rods?
4. Give the abbreviation for January and February.
5. Name the tree on which bananas grow.
6. How often does the century plant bloom?
7. What description can you give of the bottom of the ocean?
8. Explain the difference between a hill and a mountain.
9. What is the chief purpose of industrial strikes?
10. Describe the shoes of the native Hollander.
11. Name some uses to which electricity is put.
12. What would cause the air to escape from a bicycle tire?
13. Where is more grain raised, in the East or the West?
14. Tell what is meant by an Indian Reservation.
15. For what invention is Thomas Edison noted?
16. Name a state which has no seacoast.
17. Write the Roman numeral ten.
18. Explain the difference between export and import.
19. Explain why a corked bottle floats.
20. What substance is a good conductor of electricity?
21. Explain why Indians were afraid of firearms.
22. Explain the purpose of fire drills.
23. At what time do ocean waves become dangerous?
24. What medicine would you take to remedy indigestion?
25. What knowledge is covered by the study of astronomy?
26. Name a good restaurant in this vicinity.
27. What is the importance of large windows in stores?
28. Explain why a giraffe eats the foliage of trees.
29. How are the pages of a magazine held together?
30. Explain why the name string-bean is appropriate.
31. Name a nearby city in which there is a shipyard.
32. Name a fruit which grows in bunches.
33. Which of our Presidents went to South Africa?
34. Why are wire springs used in beds?
35. Why are books bound in stiff covers?
36. Why did the home people conserve food during the war?
37. Name an insect that has a hard shell.
38. What symbol on the United States money stands for liberty?
39. What weapons did the Indians use in warfare?
40. In what kind of weather does milk sour?
41. What streets in this city have Dutch names?
42. How does turning a ship's wheel steer the ship?
43. What nation aided us in the Revolutionary War?
44. What are some personal characteristics of the people of Japan?
45. What candy is black and good for colds?
46. Name a famous Indian Tribe.
47. Why is this building lighted by reflected light?
48. Why are most lighthouses situated on rocks?
49. Give some ingredients used in soap.
50. Why is a house built of stone superior to others?

obtained from the curve in Fig. 11*c*, which gives the relation between the discrete sentence intelligibility and the syllable articulation, *S*. In these tests, the observer does not attempt to write down the sentences; he simply notes whether or not he understands what is meant, writing down a cross for each sentence he fails to get. For example, if he fails to get 5 sentences out of the 50 sentences read, he records 5 crosses, and thus observes that his percentage of correct interpretations was 90. Referring to Fig. 11*c*, it is seen that 90 per cent discrete intelligibility corresponds to only 32 per cent syllable articulation, *S*. This test shows that the syllable articulation measurements furnish a much more severe test of rooms than the complete sentences.

Acoustic Specifications for Auditoriums and Public-Address Systems. With the advent of sound motion pictures and sound-amplification (public-address) systems, a number of new acoustic problems arose. It was soon found that practically all existing auditoriums and theaters were too reverberant for satisfactory reproduction of sound. Shorter times of reverberation were specified than had been the practice, and as a consequence, absorbing materials were installed more abundantly than before. Rear walls were given special attention in regard to shape and absorbing materials to reduce the reflection of the powerful beams of loud-speaker sounds directed at these walls.

These new developments involved purchases of equipment and materials, so that it became necessary to consider specifications in accordance with the usual business practice. At the present time, no standards have been agreed on, but the problem is being studied by various committees. While most of the detailed specifications concern sound instruments and equipment, it is also necessary to set up prescriptions for room acoustics. The following statements indicate the trend of specifications.

1. The time of reverberation should be adjusted by a suitable arrangement of sound-absorbing materials to give the prevailing optimal values.

2. The surfaces of the room should be designed so that the sound reflected from them should not produce pronounced echoes, concentrations, or " dead " spots.

3. The sound-amplifying system should be capable of delivering a specified intensity level to all parts of the auditorium for a specified range of frequencies; its noise level should not exceed a specified value; any distortion by the system should not exceed a specified percentage over a specified frequency range when delivering sound at a specified level, the system should provide an articulation of a specified percentage in the presence of a specified noise level; the distribution of sound in

the auditorium should not vary more than a specified amount from the average over a specified range of frequency; the microphones used should be of a specified quality, they should not have more than a specified noise, and they should have specified directional qualities.

CHAPTER XII

ABSORPTION OF SOUND BY MATERIALS

Importance of Absorption. The absorption of sound in a room is a vital consideration in securing good acoustics. Irregularities in the shape of the walls, columns, coffering, and similar devices may break up the regular reflection and make the resultant sound more diffuse, but absorption must take place to convert the sound energy into heat.

Sound-Absorbing Materials. Since the usual building materials used in a room are plaster, wood, and glass, all of which absorb only about 3 per cent of the incident sound, it has become necessary to develop various materials with greater absorption. Most of these materials are effective because of their porosity, but some products absorb energy when they vibrate, particularly when backed by an air space.

How Sound Is Absorbed. The ultimate fate of sound energy is to be converted into heat. In traveling through the air, sound waves progress by an oscillation or " quivering " of the air that sets up a friction between neighboring air particles. The amount of absorption in this process becomes noticeable for sounds above about 6,000 cycles per second, but for lower frequencies it is usually negligible in comparison with the surface absorption in rooms.[1]

On striking a solid material, the sound waves experience a friction greater than when traveling in free air, because the air particles stick to the solid surface and resist any attempt to move them. The thickness, h, of this friction layer is small, being given by the equation: $h = 0.51/\sqrt{f}$ inches,[2] where f is the frequency of the sound passing parallel to the surface of the solid. As an example, for an average sound of frequency of 400 cycles per second, the thickness h is calculated to be 25/1,000 inch. Sound waves passing into a tube would thus experience a considerable friction, particularly if the diameter of the tube were small, comparable with the dimension just given. Porous materials will thus absorb sound, and if the sizes of the pores vary, a range of frequencies will be affected. Larger intercommunicating channels in a porous material will allow sound rather free access to the interior where a considerable area of pore openings will increase the absorption.

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[1] Knudsen, *Jour. Acous. Soc. Amer.*, Vol. 3, p. 126, 1931.

[2] Lamb, *Dynamical Theory of Sound*, §66.

Sound Absorption Tests. When making calculations for the control of reverberation in rooms, it is necessary to know the absorbing values of various materials. This information is obtained by laboratory tests. The first serious attempt in this direction was the development of a method by Wallace Sabine that has been used extensively since his time. The procedure is to install 70 to 100 square feet of a sample material on the floor of a reverberation chamber, and then measure the time of decay of various pure sounds both with and without the material.[1] This arrangement approximates an installation in an actual auditorium. However, because of the small volume of the chamber, resonant modes of vibration are set up, particularly at low frequencies, that give coefficients that are larger than the values that apply to auditoriums. For higher frequencies, above 1,000–2,000 cycles per second, a " diffuse " mixture of sound is obtained in the chamber, and the resulting coefficients need no correction when used for calculating reverberation times for large rooms.

Recent Experiments. At the present writing, a more satisfactory determination of absorption coefficients is being attempted by means of " acoustic impedance." This quantity may be determined by exploring the standing waves set up when a steady beam of sound is directed against a sample mounted at one end of a tube. Since the acoustic impedance is related to the absorption of sound by the material, it is possible to develop formulas by which the absorption coefficient may be found and then used for calculations in the correction of acoustics of auditoriums. This method has an advantage over the reverberation chamber method because the acoustic impedance can be measured in different laboratories with results that agree within the usual experimental error, and the corresponding absorbing coefficients will show the same agreement, but the reverberation chamber measurements depend on the shape and size of the chamber, and the results obtained in different laboratories vary considerably. This problem is not solved completely at the present time, but much progress has been made.[2]

Acoustical Materials Association. This lack of agreement in the values of absorption coefficients as determined in the reverberation chambers of the different laboratories has proved embarrassing to the manufacturers of acoustic materials. Accordingly, they decided to form an organization and arrange to have all their materials tested in a single laboratory, which would have the advantage that the coefficients would thus be comparable. A considerable body of data was obtained by the reverberation method, and the results are published from time to time in a series of bulletins to give up-to-date information. While the coefficients for low frequencies appear too great, as already explained, the average value of the coefficients for all the test frequencies has the advantage that it represents the relative efficiencies of the various materials and thus affords a basis for competition in selling. The material in the bulletins is too extensive for reproduction in this book, but the publications can be obtained by addressing the association.[1] One sample set of data is copied from *Bulletin* VII of the association in Table 12*a*.

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[1] *Collected Papers on Acoustics*, Harvard University Press, 1922.

[2] Beranek, *Jour. Acous. Soc. Amer.*, Vol. 12, p. 14, 1940; Bolt, *Jour. Acous. Soc. Amer.*, Vol. 12, p. 217, 1940.

TABLE 12*a*

COEFFICIENTS OF ABSORPTION AT VARIOUS FREQUENCIES

	Coefficients					Noise-Reduction Coefficient
Frequency	128	256	512	1,024	2,048	
Material	0.11	0.37	0.88	0.81	0.74	0.70

The coefficients are determined for five frequencies, and an average is taken of four of them (256–2,048) to give the "noise-reduction coefficient," which is used to express the relative sound-absorbing efficiency of the material. In addition to the data shown in the tabulation, the *Bulletin* gives the following information:

> The material is in the form of cast units having a surface composed or resembling small uniform granules. The binder may be gypsum or any other suitable mineral binder; it is $\frac{3}{4}''$ thick; weighs 1.69 lbs/sq ft; is nailed to 1″ × 2″ wood studding 12″ o. c.; its surface is painted with oil-base paint having a light reflection value of 65–61 per cent.

Bureau of Standards. The Staff of the Acoustical Laboratory of the Bureau of Standards has for years conducted extensive experiments on the sound absorption of materials. The tests are similar to those just described, but their reports cover more materials than the reports of the Acoustical Materials Association, with added information about the acceptability of products for installation on government jobs. These reports, which are published annually, are labeled: "Sound

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[1] Acoustical Materials Association, 919 N. Michigan Ave., Chicago, Illinois.

Absorption Coefficients of the More Common Acoustic Materials" and "Classification of Acoustic Materials." The reports for 1941 will have the numbers: LC-632 and LC-633, and can be purchased for five cents each from the Superintendent of Documents, Washington, D. C.

Types of Absorbing Materials. Absorbing materials may be classified in four groups. *Soft materials* like hairfelt are good absorbers, since they have the desired porosity with intercommunicating larger channels. Hairfelt was used extensively in the first attempts at sound control, but it has been largely superseded by other materials, such as rock wool and asbestos, that are more fireproof, vermin proof, better looking, etc. In a description of acoustic phenomena, in the Antarctic, Poulter stated that snow was a good absorber of sound. In a tunnel of snow, 15 feet long and 7 feet high, an observer at one end could not hear the talking of a person at the other end. The granular, porous structure of snow is thus similar in absorbing action to hairfelt. *Semi-hard materials,* in the form of porous fiber boards that are stiff enough to be handled like lumber, serve simultaneously as sound absorbers and building panels. Fiber tile, 1 foot square and sometimes larger, are

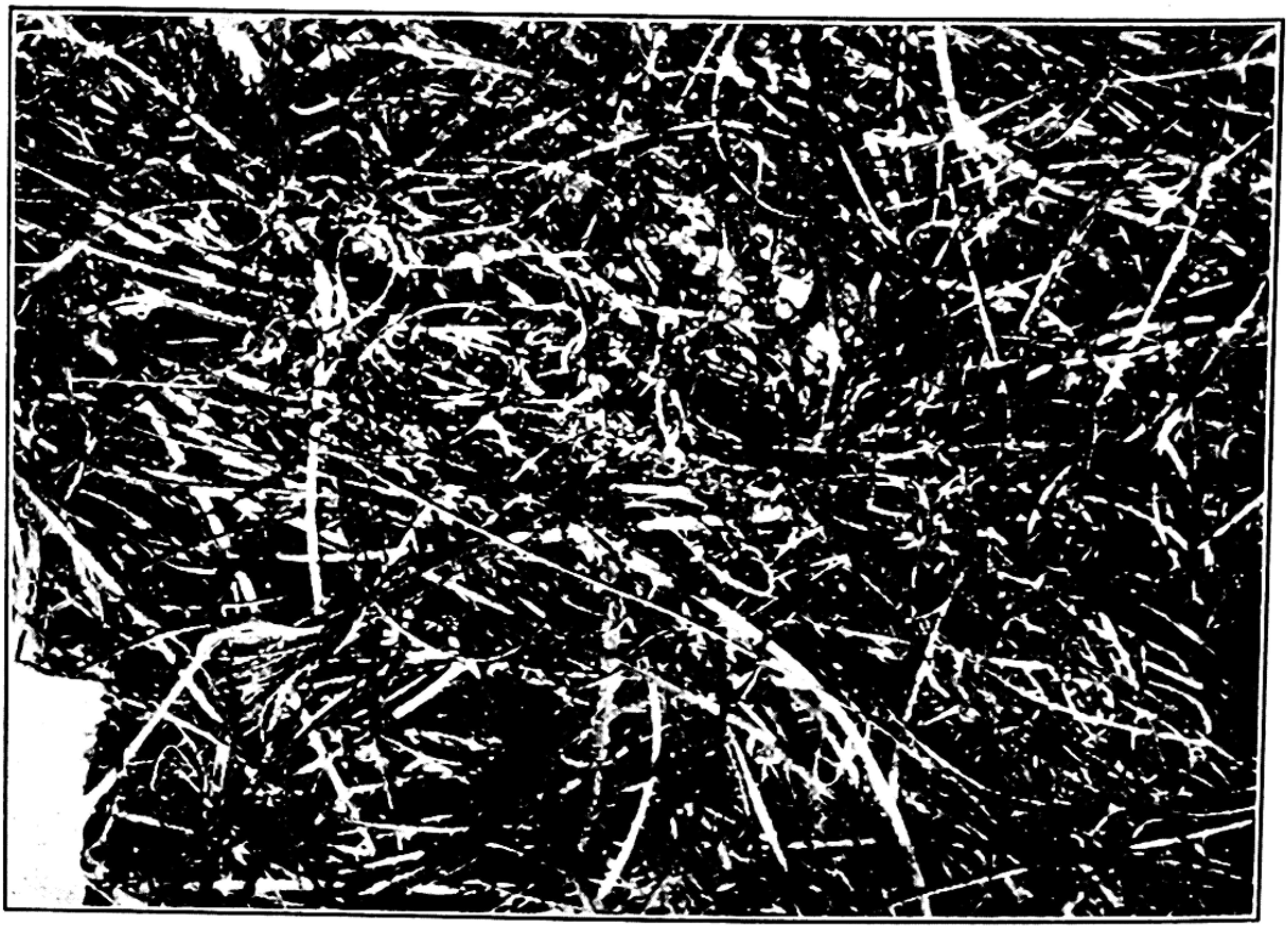

FIG. 12*a*. Photograph of hairfelt, which is a good absorber of sound because of its porosity and intercommunicating channels. Susperseded largely by other materials.

made of various materials and applied to plaster and other surfaces, or else nailed to wood studding. *Hard materials* are also made up into porous tiles of masonry and other products and installed on wall surfaces. *Acoustic plasters* have the advantage that they resemble ordinary plaster and can be used where tiles will not accord with the architectural design. They have the disadvantages that their absorbing value depends on the skill of the workman installing them, their efficiency is generally less than that of other products, and they must be painted or decorated according to special instructions so as not to close the pores.

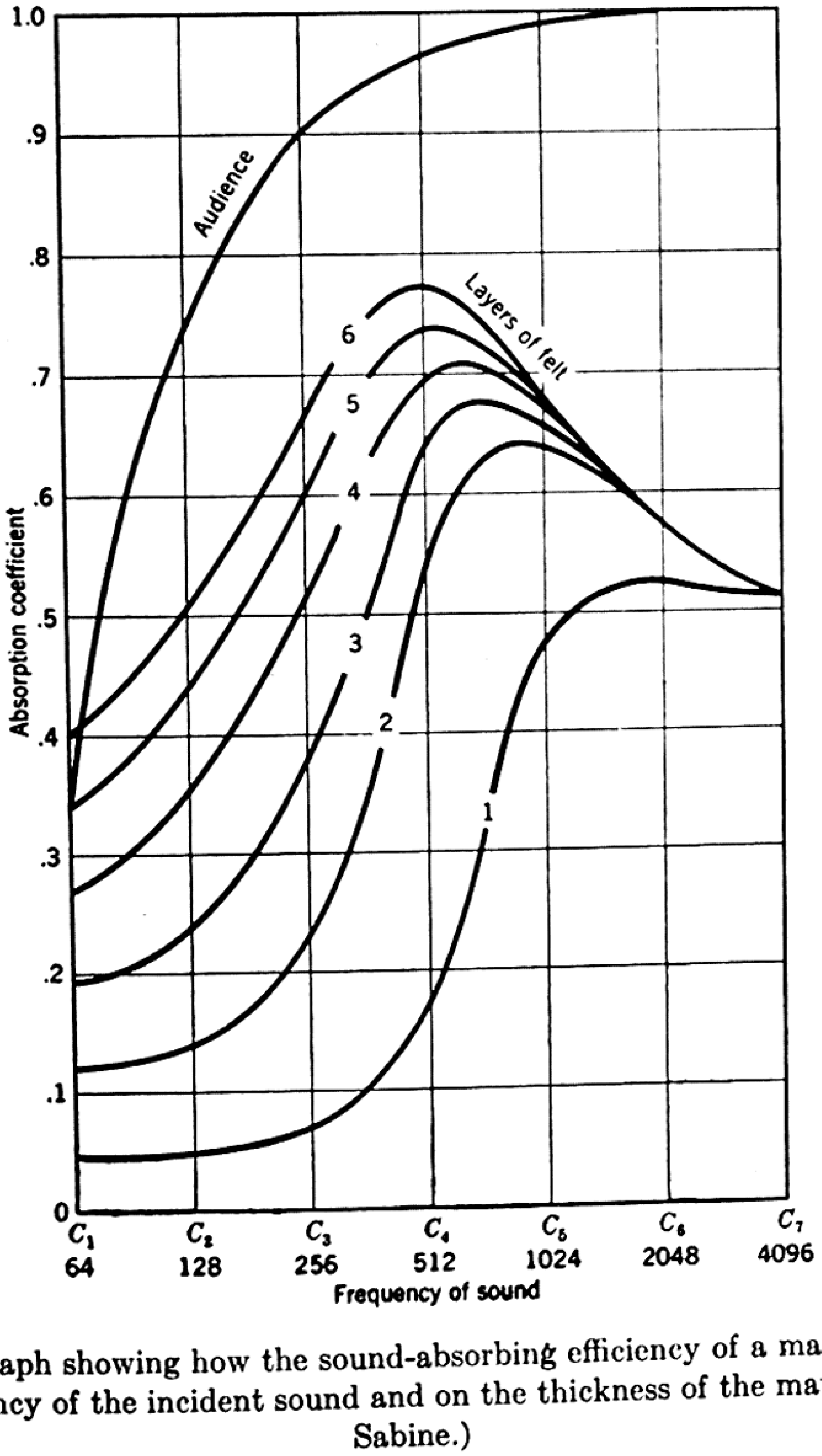

FIG. 12*b*. Graph showing how the sound-absorbing efficiency of a material depends on the frequency of the incident sound and on the thickness of the material. (W. C. Sabine.)

In addition to the four classes of materials described, there are a number of special constructions. For example, boards completely perforated with small holes are mounted in front of various absorbing materials, an arrangement that has the advantages that the front surface of the board will present a good appearance and it can be painted if the holes are not closed. Sound passes with small loss through the holes to the absorbing material back of the perforated board. One product has small holes bored directly into the absorbing material, thus omitting the front board. Material mounted out from the wall with an intervening air space generally absorbs more sound than if

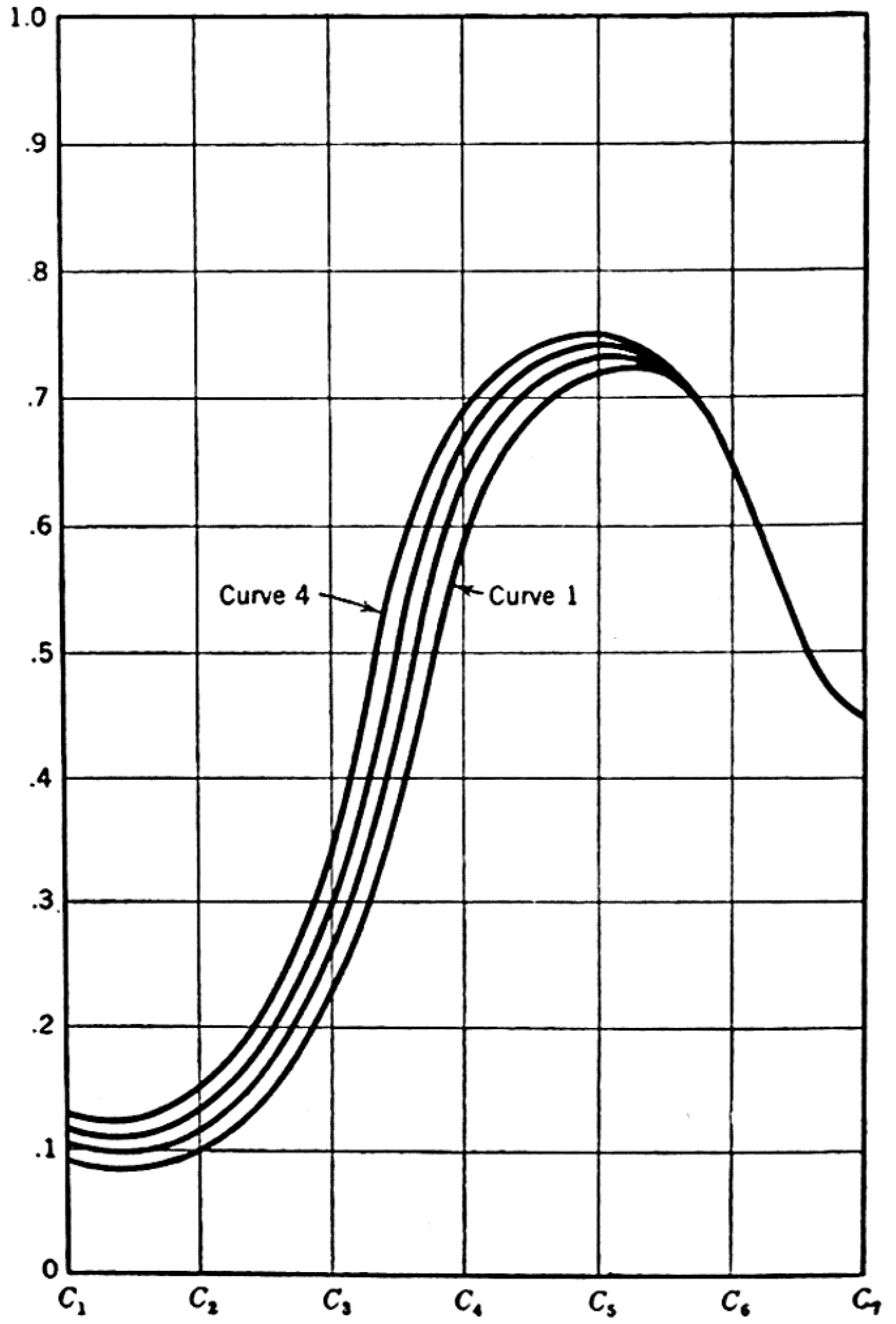

FIG. 12c. Curves showing the increase in absorption of sound with an air space between hairfelt and a wall. Curve 1 touches the wall, curve 4 is 6 inches from the wall, the other two are 2 inches and 4 inches respectively from the wall. (W. C. Sabine.)

applied directly to the wall, with resonant absorption in certain low-frequency regions.

Desirable Properties of Absorbing Materials. There is no perfect material suited to all conditions, so that an intelligent choice must be made to satisfy the requirements of the special problem. Properties that should be considered in making this choice are: sound-absorbing efficiency, cost of material and labor, durability and permanency of installation, appearance, fireproof and vermin-proof qualities, weight, and reflection of light. Painting and decorating are important matters, since these operations should not close the openings exposed to the action of sound.

Variation of Absorption. In Fig. 12*b* are shown the data obtained by W. C. Sabine for hairfelt. It is to be noted that the absorption values are greater at high frequencies than low; they increase with the thickness that range in the data of Fig. 12*b* from 1 layer of 1.1 cm (0.43 inch) to 6.6 cm (2.60 inches), the maximum absorption shifting toward the lower frequencies for the thicker samples. Data are shown also for an audience; they indicate the effective absorption due to the clothing worn; an audience might be regarded as a very " thick " material with open spaces lining the floor.

Figure 12*c* portrays the effect of an air space between a material and the wall, showing an increase of absorption of about 16 per cent at the frequency of 512 cycles per second. The use of an air space to increase the absorption has received attention in recent experiments, where it has been found that flexible wall boards and similar materials backed with an air space have given resonant absorption, particularly at low frequencies where the usual materials are not so efficient as at higher frequencies.

Coefficients for Common Materials. For convenience in calculating the reverberation in rooms, the following table gives absorption coefficients for materials in common use.

TABLE 12*b*

COEFFICIENTS OF ABSORPTION FOR COMMON MATERIALS COPIED IN PART FROM TABLE III OF *Bulletin* VII OF THE ACOUSTICAL MATERIALS ASSOCIATION

Material	*Coefficients*		
Frequency	128	512	2,048
Brick wall, painted	0.012	0.017	0.023
Same unpainted	.024	.03	.049
Carpet, unlined	.09	.20	.27
Same, felt lined	.11	.37	.27
Fabrics, hung straight			
Light, 10 oz per sq yd	.04	.11	.30
Medium, 14 oz per sq yd	.06	.13	.40
Heavy, draped, 18 oz per sq yd	.10	.50	.82
Floors			
Concrete or terrazzo	.01	.015	.02
Wood	.05	.03	.03
Linoleum, asphalt, rubber, or cork tile on concrete		.03– .08	
Glass	.035	.027	.02
Marble or glazed tile	.01	.01	.015
Openings			
Stage, depending on furnishings		.25– .75	
Deep balcony, upholstered seats		.50–1.00	
Grills, ventilating		.15– .50	
Plaster, gypsum or lime, smooth finish on tile or brick	.013	.025	.04
Same on lath	.02	.03	.04
Plaster, gypsum or lime, rough finish on lath	.039	.06	.054
Wood panelling	.08	.06	.06

ABSORPTION OF SEATS AND AUDIENCE

Audience, seated, units per person, depending on character of seats, etc.	1.0 –2.0	3.0 –4.3	3.5–6.0
Chairs, metal or wood	0.15	0.17	0.20
Pew cushions	0.75–1.1	1.45–1.90	1.4–1.7
Theater and auditorium chairs			
Wood veneer seat and back		0.25	
Upholstered in leatherette		1.6	
Heavily upholstered in plush or mohair		2.6 –3.0	
Wood pews		0.40	

CHAPTER XIII

CALCULATIONS IN ACOUSTICAL CORRECTION

Factors in Acoustic Correction. The important elements in the correction of the acoustics of an auditorium are, first, the elimination of echoes and focal concentrations that set up unequal distribution of sound in the room, and second, a reduction in the time of reverberation. Uniformity in the distribution of sound, which means the avoidance of echoes and similar disturbances, is brought about by adjusting the shape of the auditorium and its interior surfaces so as to control the reflection of sound. The reduction in the time of reverberation is usually accomplished by installing sound-absorbing materials, but there are other possibilities, as discussed in the following paragraph.

Factors That Reduce the Time of Reverberation. According to Sabine's equation $t = 0.05\ V/(as)$, it may be seen that the time of reverberation depends on three factors: the volume V of the room, the total absorption (as), and the number 0.05, the last being fixed by the assumption that the original sound level drops 60 db in the time t. Theoretically, the time t may be decreased by reducing any one of the three factors. Let us consider these possibilities. For example, suppose that, in a room of 200,000-cubic-foot volume with 1,250 sabins of absorption for which the time of reverberation is 8 seconds ($t = 0.05 \times 200{,}000/1{,}250 = 8$ seconds), it is desired to reduce the time to 2 seconds. How may this be done?

(*a*) *By Reduction of Volume.* Since the time is to be reduced from 8 seconds to 2 seconds, the volume must be reduced in the same proportion, or from 200,000 to 50,000. This solution is obviously impractical; it would mean either a smaller volume, one-fourth the size of the original room with dimensions proportional to those of the larger room, or else a reduction, for example, of the ceiling height to one-fourth the original value.

(*b*) *By Reduction of the Number 0.05.* This again will be shown to be impractical. It would mean that the initial sound level of, say, 60 db, which gives satisfactory loudness, would have to be reduced to 15 db, which is so weak a sound as hardly to be heard.

(*c*) *By Increasing the Absorption* (*as*). Fortunately, this third possibility is practical. To reduce the time of reverberation fourfold means that the absorption must be increased four times, from the original value of 1,250 sabins to 5,000 sabins, or an addition of 3,750 sabins of absorption. This additional absorption could be installed on the walls and ceiling. Suppose that areas are selected for the installation that total 7,500 square feet; then the coefficient of absorption of the material needed to give the necessary 3,750 sabins would be 0.50 ($3{,}750 \div 7{,}500 = 0.50$). There are many materials that have the coefficient 0.50. Other solutions could be worked out, depending on the areas selected that need treatment and the efficiency of the absorbing material desired for installation.

Approximations in Making Calculations. When making calculations for the correction of the acoustics of an auditorium, a certain degree of approximation is allowed. For example, a variation of 5 per cent and sometimes as much as 10 per cent in the time of reverberation will be tolerated from the optimal values given in the various tables. If the smaller variation of 5 per cent be considered, it means that the values of the volume and areas of the room used in calculating t may vary as much as 5 per cent, provided that the variations are not additive.

For the auditorium just discussed, suppose that the optimal time is taken as 2.0 ± 0.1 seconds, a variation of 5 per cent. Then, for the same variation, the volume could be estimated as $200{,}000 \pm 10{,}000$ cubic feet. This means that it would not be necessary to compute every small element of volume, such as alcoves and volumes about windows and doors. In the same way, the areas leading to the value of the absorption as could vary 5 per cent, so that the absorption could be $5{,}000 \pm 250$ sabins, giving a latitude of 250 sabins in this item. In calculating the absorption (as), it should be remembered that the values of the absorption coefficients, a, are not known exactly, but are in doubt as much as 10 per cent for some materials. This means that areas of surfaces should be estimated rather closely, to less than 5 per cent variation where the coefficient of the material is in question. Care must be taken not to have the variations additive, such as the values of 210,000 cubic feet for the volume and 4,750 sabins for the absorption, which would give the value of t as 2.21, which would be a variation of 11 per cent. It is better to have the variations offset each other, such as 210,000 for the volume and 5,250 for the absorption, or 190,000 for the volume and 4,750 for the absorption, for which the variation in the value of t is negligible. These simple illustrations are helpful for guidance when making the detailed calculations.

Reduced Sketches from the Blueprints. Before actually making any calculations, the author has found it very helpful to have a reduced sketch made of the auditorium from the blueprints. Figure 13*a* shows such a sketch used for the Purdue Music Hall, with a scale of approximately 1 inch for each 40 feet, which was prepared for the author by Mr. A. S. Davis of the Supervising Architect's office of the University

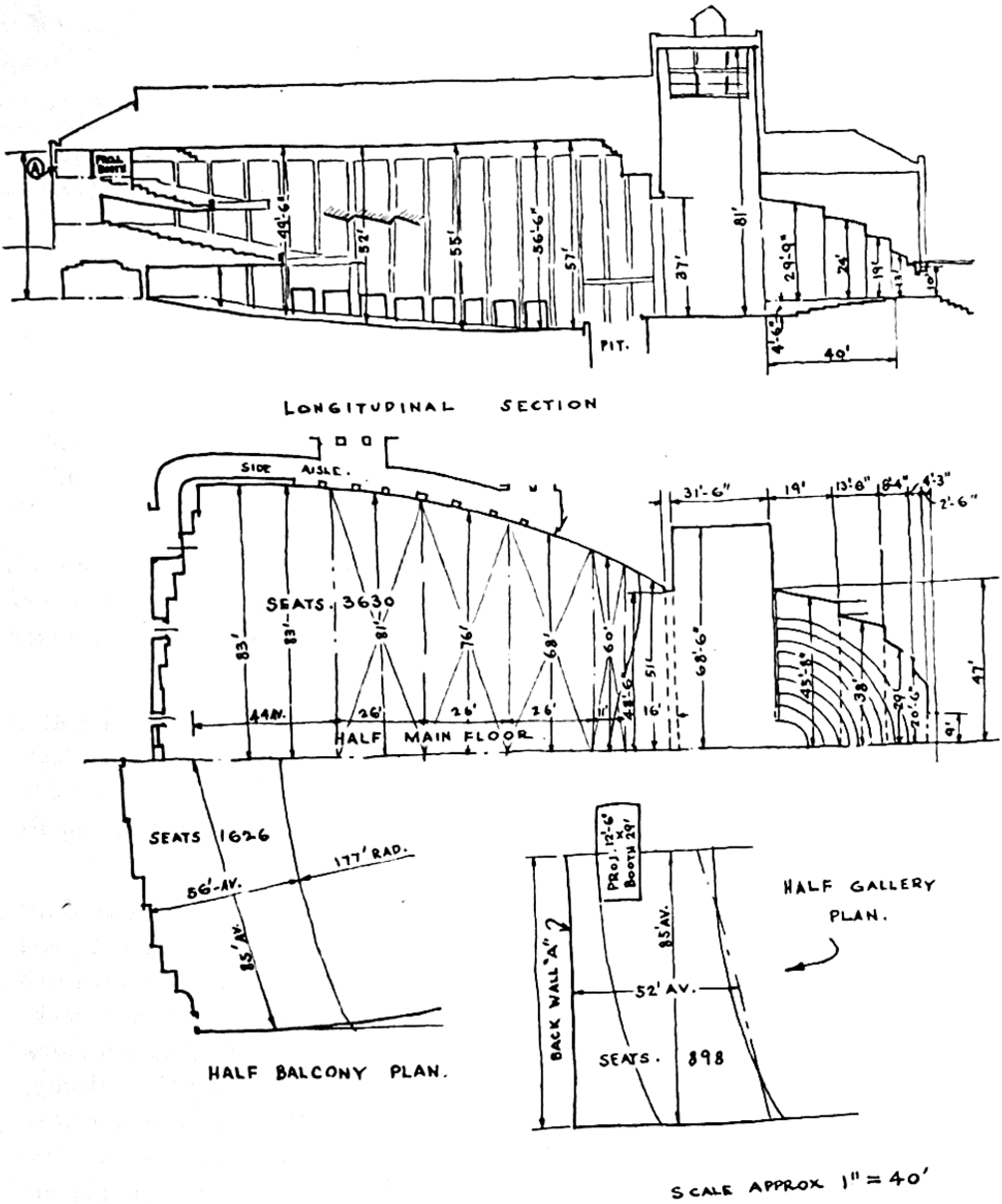

FIG. 13*a*. Reduced rough sketch of the plan and section of the Purdue Music Hall. Such a compact sketch is very useful in making calculations of the volumes and areas of an auditorium. (Drawn for the author by Arthur S. Davis, University of Illinois.)

of Illinois. The sketch need not be made exactly to scale, but it should show the plan and section of the room with the variations in the walls, and also the important dimensions from which the calculations can be made.

Examples. (*a*) In Table 5*a*, it may be seen that the absorption of the metal and glass together, 16.5 sabins, is less than 3 per cent of the total value, 567 sabins, so that it is useless accuracy to calculate these items.

TABLE 5*a*

Sound Absorption in an Auditorium

Material	Area (*s*) square feet	Coefficient (*a*)	Absorption in sabins	
			(*as*)	Total (*as*)
Wood	6928	0.03	211.	
Plaster	7440	.033	246.	
Metal	628	.01	6.3	
Glass	408	.025	10.2	
Seats	550	.17	93.5	
Total absorbing value of bare room			567.	567.
" " " " " " (in round numbers)				570.

(*b*) Suppose that a wall in a room is made up of plaster with wood trimming and wood doors. Since the absorption of the plaster and the wood are such that their coefficients are practically the same, the wall might be considered as uniform with an average coefficient of, say, 0.03.

(*c*) Consider a side wall with windows. The coefficient for the plaster is 0.033, and the coefficient for the glass is 0.027. Usually the area of the glass is small compared with that of the plaster, so that the entire wall could be figured with a coefficient of 0.033, thus making it unnecessary to compute separately the area of the windows.

(*d*) Consider a balcony at the rear of a rectangular room. The areas of the risers of the steps need not be figured separately, but may be included as part of the area of the rear wall, assuming that they both are of practically the same absorption value. That is, suppose that a person stood on the platform looking at the rear wall, which is, say, 40 feet wide and 25 feet high, giving an area of 40 × 25 = 1,000 square feet. Part of this area is cut off by the balcony, but if the area of the wall is taken as 1,000 square feet, it can include the area of the risers, without separate calculation of the latter. In the same way, the horizontal parts of the steps may be included in the floor area, assuming again that the floor and steps are of practically the same absorbing value.

The foregoing simple illustrations show the approximations that may be made and will suggest others in the actual work. Beginners usually make calculations that are too detailed, and thus sometimes lose sight of the larger items. For example, consider again the calculations given in Table 5*a*. The total absorption needed for the optimal conditions was shown to be 3,100 sabins. Assuming that the volume of the room is given correctly, since it is rectangular and easily calculated, then the 5 per cent variation could be applied to the absorption, or 155 sabins (5 per cent of 3,100). This means that the variation in the 567 sabins for the empty room could be 155 sabins, or 27 per cent. This does not mean that the calculations should be done carelessly, but they should be done intelligently.

CHAPTER XIV

ACOUSTIC ADJUSTMENT OF SMALL ROOMS

Types of Rooms. The discussion in this chapter is confined to rooms with low ceilings. The acoustic problem, except for special cases such as broadcasting rooms, concerns the reduction of noise rather than control of reverberation. For large office spaces, it will be shown that sound generated in one part of the room falls off in proportion to the distance it progresses away from the source, whereas in larger rooms with higher ceilings there is no marked attenuation of sound in any direction from the source.

The reduction of noise is generally desirable. Low-ceiling rooms, such as offices, telephone switchboard rooms, typewriter rooms, hospital rooms, etc., are usually occupied all day long, and some of them for 24 hours a day. For these occupants, the reduction of noise is not only a welcome relief but it also increases their efficiency.

Offices. Acoustical treatment of the ceiling is the usual practice for office quieting, since material installed on this area is out of the way of the occupants and does not get dirty so easily as when installed on other surfaces of the room. Where greater quiet is desired, the application of sound absorbent to the side walls is advised. A carpet on the floor is also efficient, and if the usual ½-inch-thick carpet lining is used, the absorption is practically doubled.

Noise Reduction. The degree to which noise is reduced requires some consideration. According to the reverberation theory, the average intensity of sound in a room is inversely proportional to the absorption in the room, assuming that the output of sound remains the same. For example, if the absorption is doubled, the intensity is reduced one-half; increasing the absorption 10 times will reduce the intensity to one-tenth its original value. In an equation, this relation is expressed as: $I_1/I_2 = a_2/a_1$, where I_1 and a_1 are respectively the intensity and absorption initially, and I_2 and a_2 are these factors after the absorption has been changed from a_1 to a_2. The amount of noise reduction is usually measured in decibels, as explained in Chapter I. That is, a reduction in intensity level from I_1 to I_2 is expressed in decibels as: $\text{db} = 10 \times \log_{10} (I_1/I_2)$. The decibel reduction for an increase in absorption from a_1 to a_2 is thus seen to be: $\text{db} = 10 \times \log_{10} (I_1/I_2) = 10 \times \log_{10} (a_2/a_1)$.

For example, if the absorption is increased 4 times, so that $a_2/a_1 = 4$, then the decibel reduction is: db $= 10 \times \log_{10} (a_2/a_1) = 10 \times \log_{10} (4) = 6$ db. According to Fletcher's loudness curve, Fig. 1*q*, the reduced noise would appear to be only 1/2.7 as loud as before, a noticeable difference, assuming that the noise is equivalent to a 1,000-cycle tone. Figure 14*a* gives a graph showing the theoretical decibel reduction for various ratios of a_2/a_1. The foregoing calculation does not apply exactly to Fletcher's loudness reduction in a room because noise generally is not equivalent to a 1,000-cycle tone, and the mixture of sound in the room is not in accord with the " diffuse " condition required by the reverberation theory. Nevertheless, the calculations give a fairly close idea of what to expect.

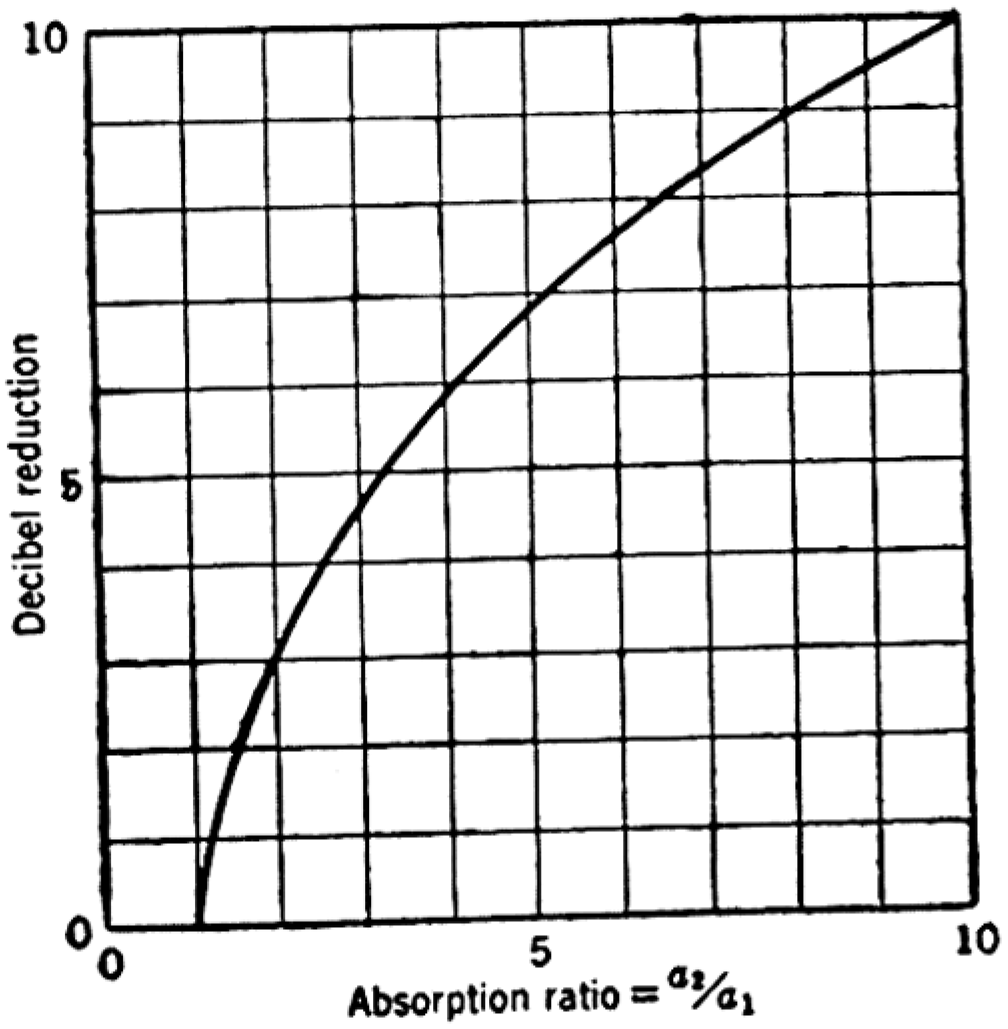

FIG. 14*a*. Graph showing the theoretical relation of the decibel reduction of sound in a room to the ratio of the total absorption in the room after treatment to the absorption before treatment.

Hospitals. In hospitals, it is usually sufficient to treat the ceilings of the corridors. Patients are supposed to be quiet, so that most of the rooms require no acoustical treatment. Some rooms, however, are noisy and these will require attention — nursery, kitchen, maternity wards, offices with typewriters, etc. Linoleum on the corridor floors is recommended, since it will reduce noise of footsteps, carts of different sorts, and metal utensils.

Broadcasting Rooms. Special arrangements are required in broadcasting rooms. To control the reverberation, it is necessary to absorb sounds of all usual frequencies. Since most materials have a broad resonant absorption from about 500 to 2,000 cycles, it is necessary to make added provision to absorb the low frequencies. The requirements in this connection have already been discussed in the chapter on optimal reverberation. One means of absorbing low-frequency sound is to install flexible materials that can vibrate, and back them with an air space. Such constructions have a resonant absorption over certain low-frequency regions that may be calculated from the physical characteristics of the construction.[1] The control of sound in broadcasting rooms is accomplished by installing rectangular sections of different absorbents in irregular fashion on the walls and ceiling, thus absorbing and diffracting the sound and reducing the normal mode resonances by minimizing the reflections between parallel walls. Figure 14*b* shows one room adjusted in this manner.

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[1] R. Rogers, *Jour. Acous. Soc. Amer.*, Vol. 10, p. 280, 1939.

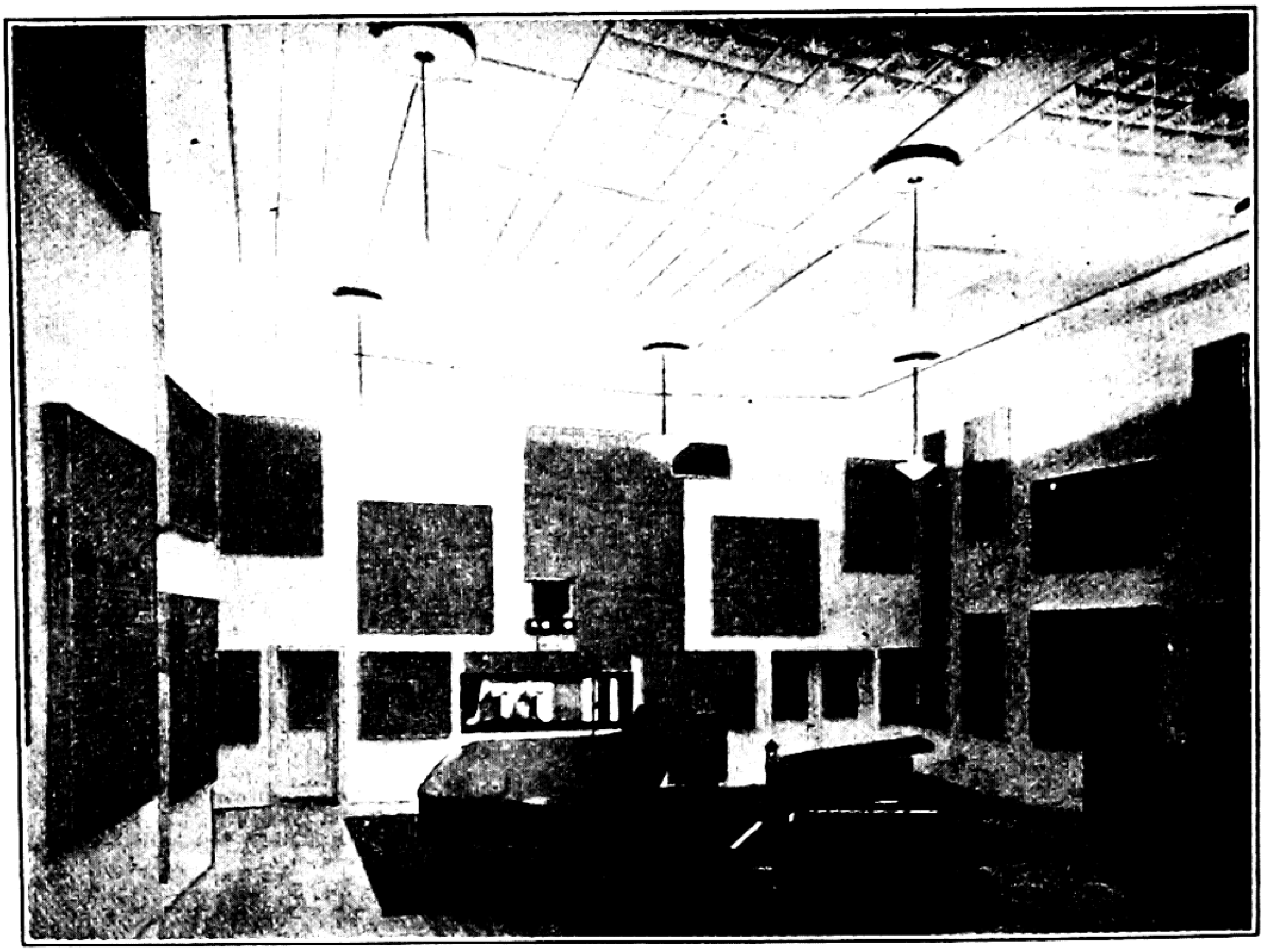

Fig. 14*b*. Photograph showing the special arrangement of absorbing materials in a broadcasting room to control the sound. (Potwin.)

Lined carpets on the floor of these rooms add to the absorption. In some rooms, reflecting walls are placed near the performers so that they can hear themselves, the microphone being placed in a less reverberant space. Curtains that can be drawn over certain walls are useful in adjusting the reverberation for different broadcasts. Figure 14*c* shows an arrangement described to the author by Mr. R. F. Norris, by which a performer was able to hear himself. The room

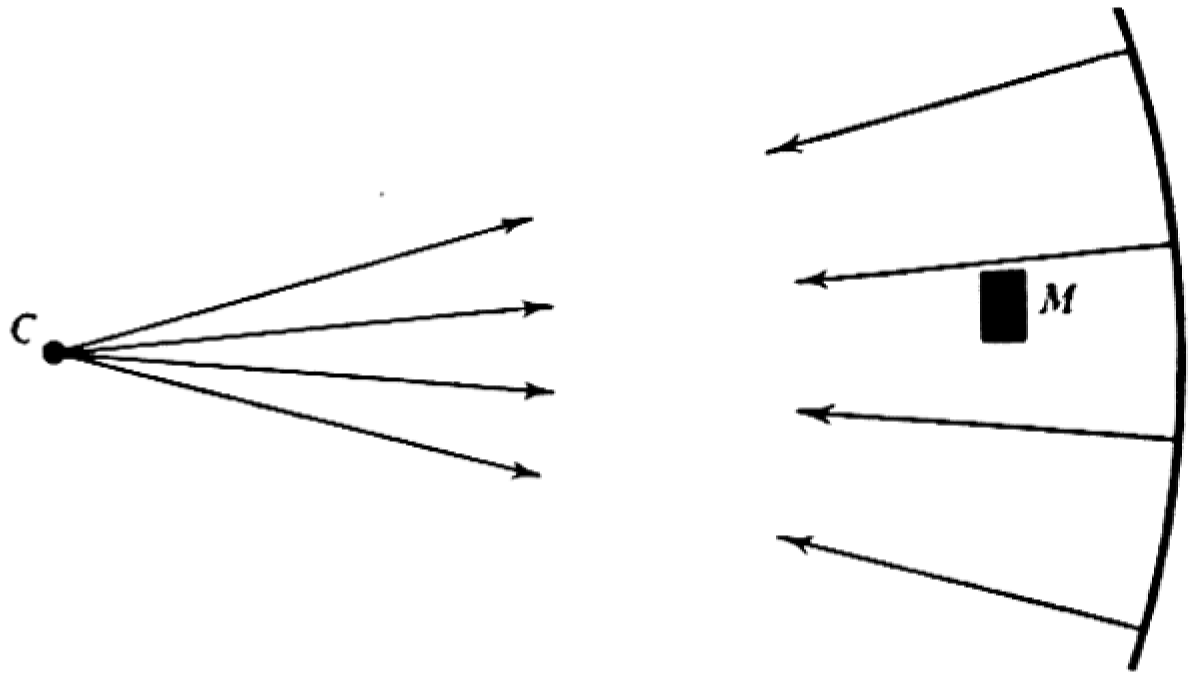

Fig. 14*c*. Arrangement in a broadcasting room by which a curved reflector sends sound back to the performer, *C*, so that he can "hear himself" and thus adjust his performance for best effect. (Norris.)

was deadened in the usual fashion, and a curved screen was installed. Sound from a performer at C passed to the screen and was reflected and focused at the starting point C. Performers using this device preferred to stay at the focal point. The microphone M gets the direct sound but not the reflections.

Large Office Rooms. In large offices, such as those occupying an entire floor of a building, the average intensity of sound is not uniform throughout the room, as is assumed approximately for large auditoriums. It is found that the sound is attenuated as it passes from the source to other parts of the room, probably because of vertical reflections of the sound waves between the floor and the ceiling. The conditions are somewhat similar to those when sound spreads out in a wide, shallow ventilating duct. Figure 14*d* gives some experimental data showing how the sound is attenuated in large offices with low ceilings. In the experiments, a loud-speaker at one end of the room furnished sound that was measured by an audiometer method at various distances from the source, the measurement at a point 1 foot distant from the source being taken as the basis of comparison. It is to be noted that the sound falls off rapidly, being reduced some 15 db at a point 10 feet from the source. This means that conversation at a desk in the room would not be perceived a few feet away above the general office noise; that is, sounds tend to be localized. It is also to be noted that the attenuation takes places both with and without ceiling treatment, but that the ceiling treatment adds decidedly in reducing the

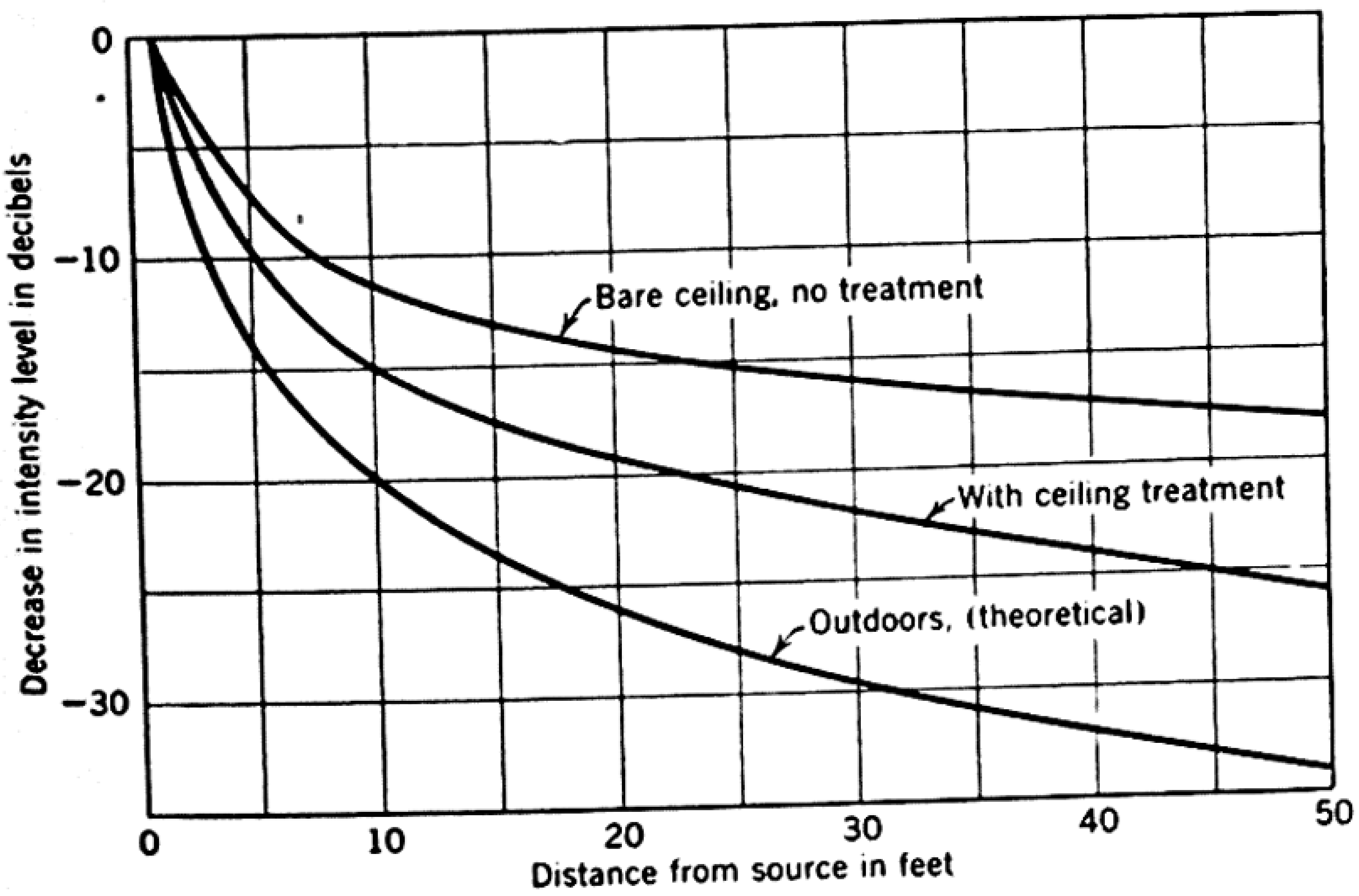

FIG. 14*d*. Absorbing material on the low ceiling of large office rooms reduces the noise. (Waterfall.)

sound. On the basis of his measurements, Waterfall makes the following recommendations:

HEIGHT OF CEILING	INSTALL MATERIAL ON CEILING
10 to 15 feet	With coefficient of 0.3 to 0.5
More than 15 feet	" " " 0.5 to 0.8
More than 30 feet	Treat both side walls and ceiling

Acoustic Treatment of Room with Low Ceiling. Figure 14*e* shows the usual ceiling treatment applied to rooms with low ceilings. For large office rooms of this type, it is sometimes advisable to treat the side walls also, if typewriters and other machines are located near the walls. The side-wall treatment should not extend below the chair rail, to avoid accidental damage by occupants of the room.

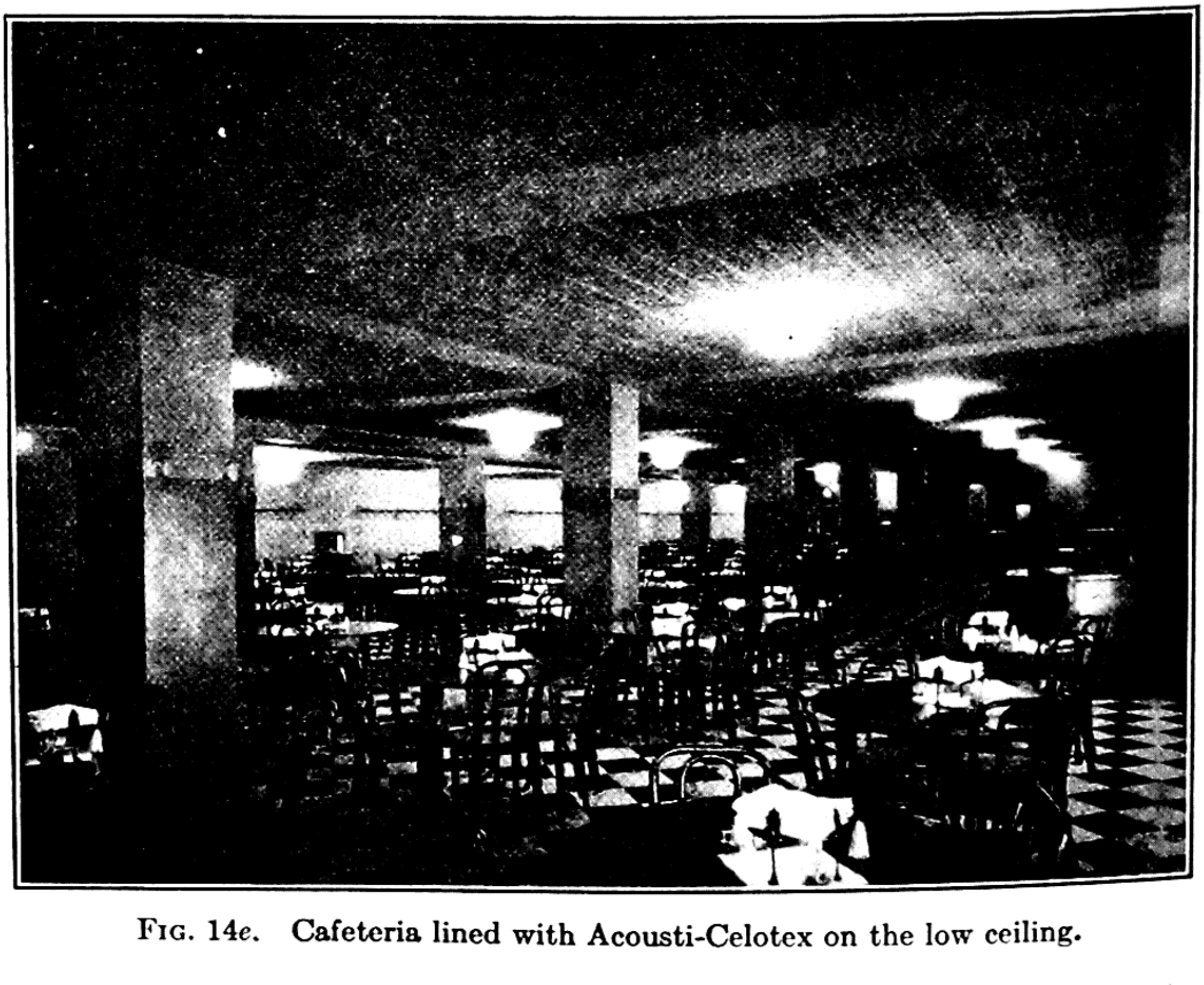

FIG. 14*e*. **Cafeteria lined with Acousti-Celotex on the low ceiling.**

Partitioned Offices. Sometimes large office spaces are divided more or less into smaller offices by partitions. When making this division it is usually assumed that the partitions will give privacy for sound as well as vision. This is a mistake, since sound will pass easily over the partition, even though the ceiling is acoustically treated. In order that the sound be reduced considerably, it is necessary that the partitions extend from the floor to the ceiling and that tight connections be made at the top and bottom. Sound-absorbing partitions are useful in such offices, however, if they are placed near noisy machines, even if they do not extend to the ceiling.

PART III — SOUND INSULATION

CHAPTER XV

SOUND TRANSMISSION AND INSULATION

Need for Sound Insulation. The demand for quiet rooms in hospitals, hotels, and office buildings; the desirability of insulating music rooms and studios where disturbing sounds are produced; and the necessity for solving similar problems in the control of noise have aroused the interest of acoustical engineers. In recent years, a number of investigators have studied the theoretical and experimental phases of the problems, have taken measurements that have resulted in various tables of data for the sound-insulating values of materials and constructions, and have made practical installations in buildings with successful results.

Two Types of Sound. The general problem of sound insulation involves a consideration of two types of sound: first, sounds that are generated in the air and progress through the air; and second, those that originate and progress in the solid parts of the building structure. For example, a typewriter makes " clicking " sounds due to the impact of the keys on paper. These sounds travel in the air and soon fill a room with this disturbance. At the same time, the typewriter carriage makes a " bump " when it is stopped after each click that is communicated to the table, then to the floor by the table legs, and through the floor to other parts of the building structure where this bump sound may be heard by occupants in other rooms.

Insulation of Sounds in Air. Sounds in the air may be set up by a violin, the voice, a clarinet, etc., and then proceed outward from the source through the surrounding air to the boundaries of the room. Here the energy may be transmitted to an adjoining room in three ways:

1. By passing through the air passages in ventilator pipes or other openings.

2. By setting the separating wall in vibration so as to create sound waves on the further side.

3. As an elastic wave motion in which the pressures and rarefactions of the sound waves are transmitted from particle to particle in the wall and are communicated to the air on the further side. Experience shows that the escape of sound is usually greatest through the ventilation

ducts, and that, unless these vents are arranged in some special manner to hinder the transmission, it is a waste of effort to install soundproof walls or floors or other special constructions. Next in importance to the ventilation system in the transmission of sound is the vibration of walls. Sound pressures and rarefactions in one room set a wall in mechanical vibration, and the wall, in turn, sets up sound waves in the air on the further side. The action is more marked if the wall is thin or if it is in tune with the sound. The amount of energy transmitted by elastic waves is usually small compared with the transmission by the vents and by wall vibrations. Sounds in air are quite effectively stopped by fairly massive, rigid walls that do not have openings for pipes or ventilators. Such a wall stops sound because it presents a new medium, varying decidedly in density and elasticity from the air.

Vibrations in the Building Structure. The other sounds to be considered in soundproofing are the vibrations generated by motors, pianos, elevators, street traffic, etc., which are in direct contact with the building structure and which travel easily through the continuity of solid materials and, by setting up resonant movements in partitions or furniture, may create sound waves in air. It is more difficult to stop vibrations progressing in the building structure than those passing through the air. The effective method of control, as for the sounds in air, lies in the interposition of a discontinuity in the path of the waves. For instance, an air space in masonry is theoretically an effective barrier because of the marked discontinuity in elasticity and density between masonry and air. Practically, however, this arrangement is not effective because the discontinuity is not complete, the weight of materials necessitating a contact across the air space that allows easy transfer of the vibrations. An approximate solution is obtained by inserting air-filled materials, such as hairfelt, flax, or sand, which, though lacking the rigidity of solids, are still able to sustain a considerable load, and, because of the enclosed air, make a fairly complete break in the continuity of structure. Chapter XVI describes a method by which elastic springs may be interposed to reduce transfer of vibrations.

Important Elements in Sound Insulation. According to the foregoing analysis, which is based on the theory of the subject, on experimental investigations, and on a consideration of practical constructions, the important elements to be sought for in soundproofing are:

1. A massive and rigid building structure to minimize vibrations.
2. Control of sound in ventilator ducts and other air passages.
3. Control of progress of vibrations in the building structure by means of continuities, sound-absorbing materials, and springs.

The methods by which these essential features of soundproofing are secured will be discussed in succeeding portions of the text.

Theory of Sound Transmission. The numerical value of the amount of sound reduction by a partition is obtained in accordance with the following considerations. The simplest conception is called the transmittivity, τ, which is defined as the ratio of the intensity of the sound transmitted by the partition, I_2, to the intensity of the sound incident on the partition I_1; that is, $\tau = I_2/I_1$. For practical purposes, the reciprocal of τ is taken, which shows how much the sound is reduced by the partition; it is usually expressed in decibels and is called the transmission loss, T. L., as follows:

$$\text{T.L.} = 10 \times \log_{10} \frac{1}{\tau} = 10 \times \log_{10} \frac{I_1}{I_2}$$

For example, suppose the fraction of sound transmitted to be 1/1,000; then the transmission loss would be:

$$\text{T. L.} = 10 \times \log(1{,}000) = 10 \times 3 = 30 \text{ db}$$

This would mean that a sound of 70-db intensity level would be reduced 30 db by the partition and would have only 40-db intensity level after passing through the partition. A loud radio sound of 80-db level would be reduced to 50 db by the partition, etc.

Experimental Procedure. The transmittivity is not easy to measure. The usual procedure is to install the partition under test between a " source " room and a " receiving " room, as in Fig. 15*a*. A " warble " tone in the source room emits sound which, by successive reflections, fills the room with sound so that the average energy level reaches a value E_1; that is, an equilibrium is established when just as much sound is lost by absorption and transmission at the walls as is generated by

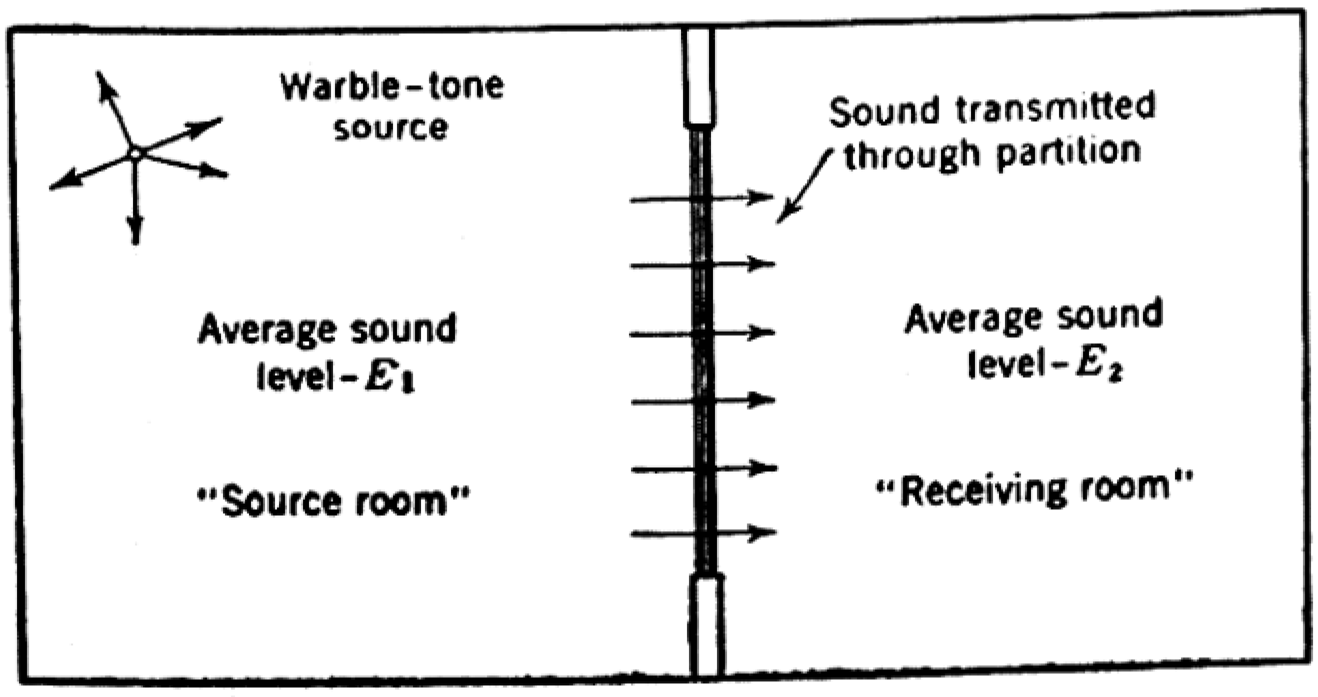
Warble-tone source
Sound transmitted through partition
Average sound level-E_1
Average sound level-E_2
"Source room"
"Receiving room"

FIG. 15*a*. Sound generated in the source room is reduced in intensity by the partition when passing through to the receiving room.

the source in the same time. During this process, a fraction, τ, of the sounds " flows " through the partition into the receiving room and builds up a reduced energy level, E_2. Davis has shown[1] that, if the source of sound is in a rather large, reverberant room and the sound is transmitted through a partition into a much smaller, deadened room, the equation which holds is:

$$\frac{E_1}{E_2} = \frac{(as)}{\tau A}$$

where (as) is the total absorption in the receiving room and A is the area of the partition. Taking logarithms, the equation becomes, in decibels:

$$10 \times \log_{10} \frac{E_1}{E_2} = 10 \times \log_{10} \frac{1}{\tau} + 10 \times \log_{10} \frac{(as)}{A}$$

The expression $10 \times \log_{10}(E_1/E_2)$ has been called the " reduction factor "; it gives the amount that sound is reduced in an actual installation, which involves the transmittivity and also the area of the partition and the absorption in the receiving room. When comparing partitions for use in a contemplated construction, it is obviously desirable to consult values for the transmittivity rather than the reduction factor, the former depending only on the partition and not on the conditions of the testing rooms.

Results of Experiments. A large amount of data on insulation of partitions has been published, some giving the reduction factors and some the transmittivity, which appears somewhat confusing. However, the drawback is not serious, and the data have been used extensively in practical installations. The results obtained are too extensive for complete reproduction, but a selection of the material is presented to illustrate the essential properties that will be useful for guidance when choosing constructions for sound insulation.

Desirable Elements in Sound Insulation. In the first place, it should be remembered that sound is transmitted chiefly by *vibrations* of partitions, assuming that all air openings and cracks are shut or controlled in some manner. It is therefore desirable to know the means by which vibrations can be minimized. For this purpose, a heavy, robust structure will be useful, since it will resist being set in motion, as is shown by the effective stopping of sound by a brick wall or a thick sheet-iron door. But brick walls and sheet-iron doors are not practical under usual conditions, so that investigations have been made to find constructions that are light in weight, small in volume, comparatively inexpensive, and yet efficient in insulation. The illustrations that follow will throw light on these questions.

---

[1] *Phil. Mag.*, Vol. 50, p. 75, 1925; Vol. 2, p. 543, 1926.

Vibrating Partitions. The author conducted an investigation with results that were quite puzzling at first.[1] Two layers of paper-lined felt transmitted *more* sound than one layer; also, the reflection was less for two layers than for one. The explanation is easily seen when the transmission and reflection are plotted together, as shown in Fig. 15*b*.

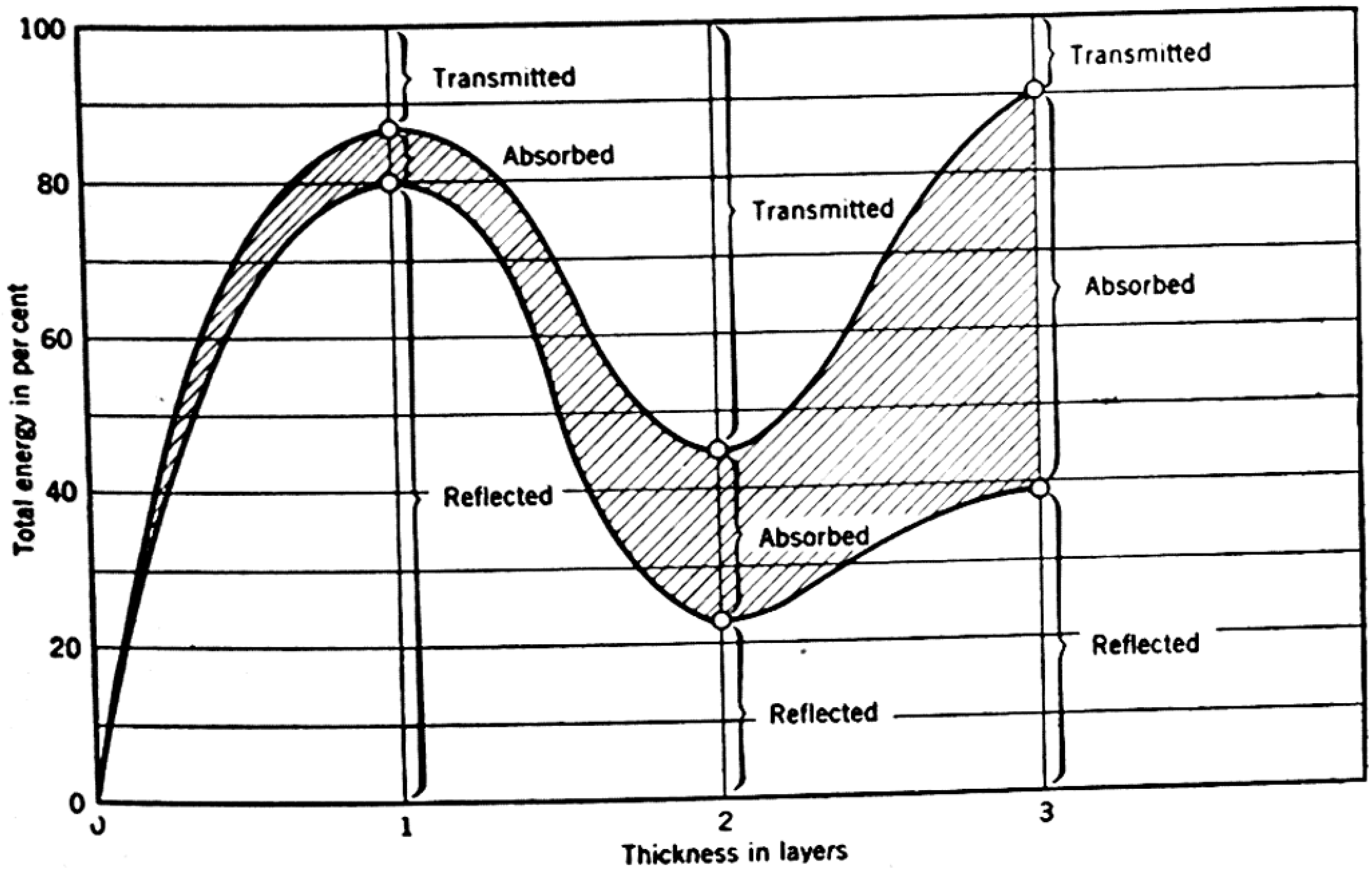

FIG. 15*b*. Anomalous action of a vibrating partition in which two thicknesses of material transmitted more sound than one partition because of the resonant vibration.

The two layers vibrated under the action of the sound and thus made the transmission disproportionately large.

Figure 15*c* shows the relative amounts of reflection, absorption, and transmission of sound by a partition that does not vibrate.

The vibration action shown in Fig. 15*b* illustrates the defect that unfortunately is present to a greater or less degree in most partitions, and accounts for a large part of the sound transmission; the vibrations are usually only a small fraction of an inch, but they transmit sound waves that are easily detected by the sensitive ear.

Effect of Air Space between Partitions. An experiment is described by P. E. Sabine[2] which shows how sound transmission is reduced by an

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[1] Watson, F. R. "An Investigation of the Transmission, Reflection and Absorption of Sound by Different Materials," *Phys. Rev.*, Vol. 7, pp. 125–132, 1916.

[2] *Acoustics and Architecture*, p. 271.

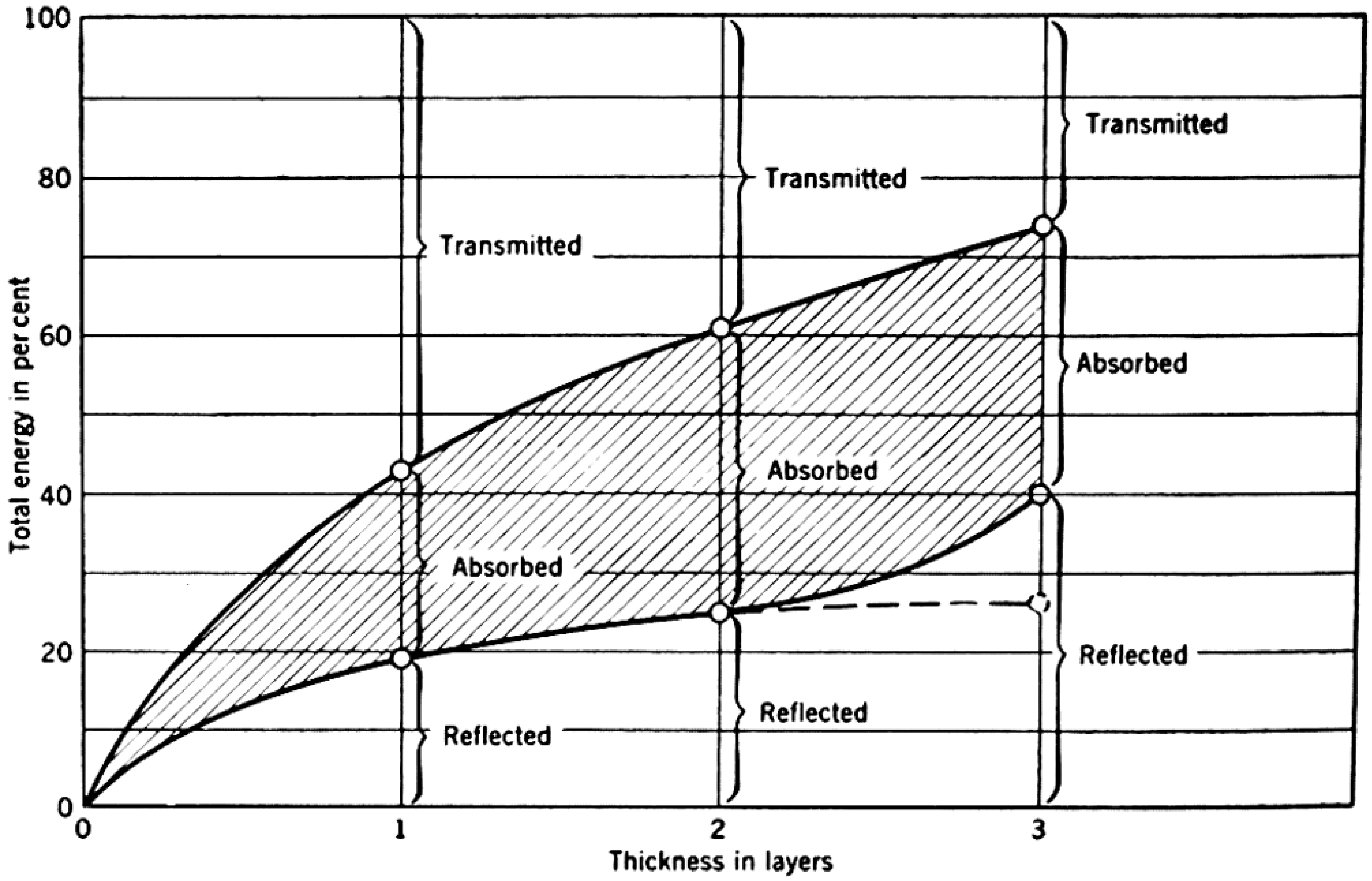

Fig. 15*c*. Relative amounts of sound reflected, absorbed, and transmitted normally by a partition of lined hairfelt.

air space. Two single-pane ¼-inch plate-glass windows, 82 by 34 inches, were set in 1-inch wooden frames, and then tested for sound insulations with increasing width of air space between them. The results are shown in Table 15*a*.

TABLE 15*a*

Insulation of Sound by Air Spaces Between ¼-Inch Plate-Glass Windows (P. E. Sabine)

Description	Reduction in Decibels
Sashes in contact	33.2
1½-inch separation	38.6
4½ " "	40.1
7½ " "	44.2
9½ " "	46.3
13½ " "	48.2
16 " "	48.8

These results show the advantage of an air space between two partitions. Heavy, stiff partitions will give greater insulation with the air space than light, easily vibrated partitions. Bridging an air space with solid materials like wood studding reduces the effect of the air space, since the two partitions then vibrate as a single unit instead of two separate units. Inserting sawdust or slag between the partitions reduces insulation, but lining the partitions with hairfelt or similar materials increases the efficiency.

Variation of Transmission with Frequency of Sound. The sample data shown in Table 15*b*, taken at the Bureau of Standards,[1] indicate how the transmitted sound varies with the frequency.

TABLE 15*b*

SOUND TRANSMISSION DATA, BUREAU OF STANDARDS

Data for wood stud partition, gypsum lath nailed to studs with nails approximately 6 inches apart, scratch and brown coats of sanded gypsum plaster, smooth, white finish thickness of plaster ½ inch.

Transmission loss (in decibels) at frequencies (cycles/sec)

											Average		Weight lb/sq ft
128	165	192	256	384	512	768	1024	2048	3100	4096	256 to 1024	128 to 4096	
32.6	...	27.8	31.0	34.9	39.2	44.3	45.6	48.7	....	65.9	39.0	41.1	15.2

The data are taken for a considerable number of low frequencies to detect any resonant action. Inspection of the results shows that the insulation depends on the frequency. For example, it is seen that there is a " dip " in the data for the frequency of 192, indicating that the partition has increased vibration at that value and transmits more sound than for neighboring frequencies. The insulation for most partitions is usually large at high frequencies; low frequencies are likely to set up vibrations and transmissions, therefore, values of the insulation at the lower frequencies should be considered carefully when choosing a partition. The Bureau of Standards Report presents a large amount of data on insulation of different partitions and floors.

Transmission of Sound by Floor. If a partition is struck with a hammer, the sound is heard much louder on the other side of the partition than the sounds of speaking and music that come to the partition through the air. In the same way, footsteps that strike the floor vibrate it vigorously and are heard in the room below. Floor constructions thus require greater insulation than partitions. The Bureau of Standards publication mentioned in the previous paragraph gives insulation data for a considerable number of floors. Generally these are heavier and thicker than partitions, with various arrangements of rough and finish floors that are " floated " on the main floor with different fiber boards, springs, loose absorbing material, etc. Suspended ceilings, hung by special devices from the under side of the floor, improve the insulation.

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[1] Bureau of Standards, Report BMS 17, "Sound Insulation of Wall and Floor Constructions." For sale by the Superintendent of Documents, Washington, D. C., price 10 cents. Also Supplement to Report BMS 17 issued Dec. 20, 1940, price 5 cents.

Insulation Data for Various Constructions. Table 15*c* presents results in typical constructions, taken from extensive tables prepared by Knudsen.[1] These data give what Knudsen designates as the " probable average value of the transmission loss," based on his critical study of the results of various investigators.

Inspection of the data in Table 15*c* shows generally that the insulation increases with the weight of the partition or floor. The few results quoted give some idea of the relative insulation values of different types of construction, but the various tables mentioned should be consulted where special insulating conditions are to be satisfied.

To be effective, partitions should have reducing values of 30 db, or more. Experience has shown the following in connection with sound reduction.[2]

> With an average reduction factor of 25 db, normal speech can be understood quite easily and distinctly through the partition.
>
> With an average reduction factor of 30 db, loud speech can be understood fairly well if conditions are quiet.
>
> With an average reduction factor of 35 db, loud speech is audible, but not easily intelligible under quiet conditions.
>
> With an average reduction factor of 40 db, normal speech is not audible, loud speech can be faintly heard but not easily understood, and for all practical purposes the partition can be considered soundproof. Separating partitions between apartments should have a factor of about 40.
>
> For piano rooms, organ rooms, etc., a better partition is sometimes needed. Higher factors than 40 are desirable for such cases.

Summary. A number of considerations affect the choice of partitions for sound insulation. In addition to the acoustic efficiency, which is, of course, important, it is necessary to consider the weight, cost, fireproofness, etc. But other acoustic factors are important. The ear is more sensitive to sounds where frequencies range from about 500 to 2,000 cycles, and the average sound level of speech and music is higher for these frequencies, so that the insulation partition should be more effective in this region than others.[3] See Figs. 6*c*–6*f*. There is also

[1] *Architectural Acoustics.*

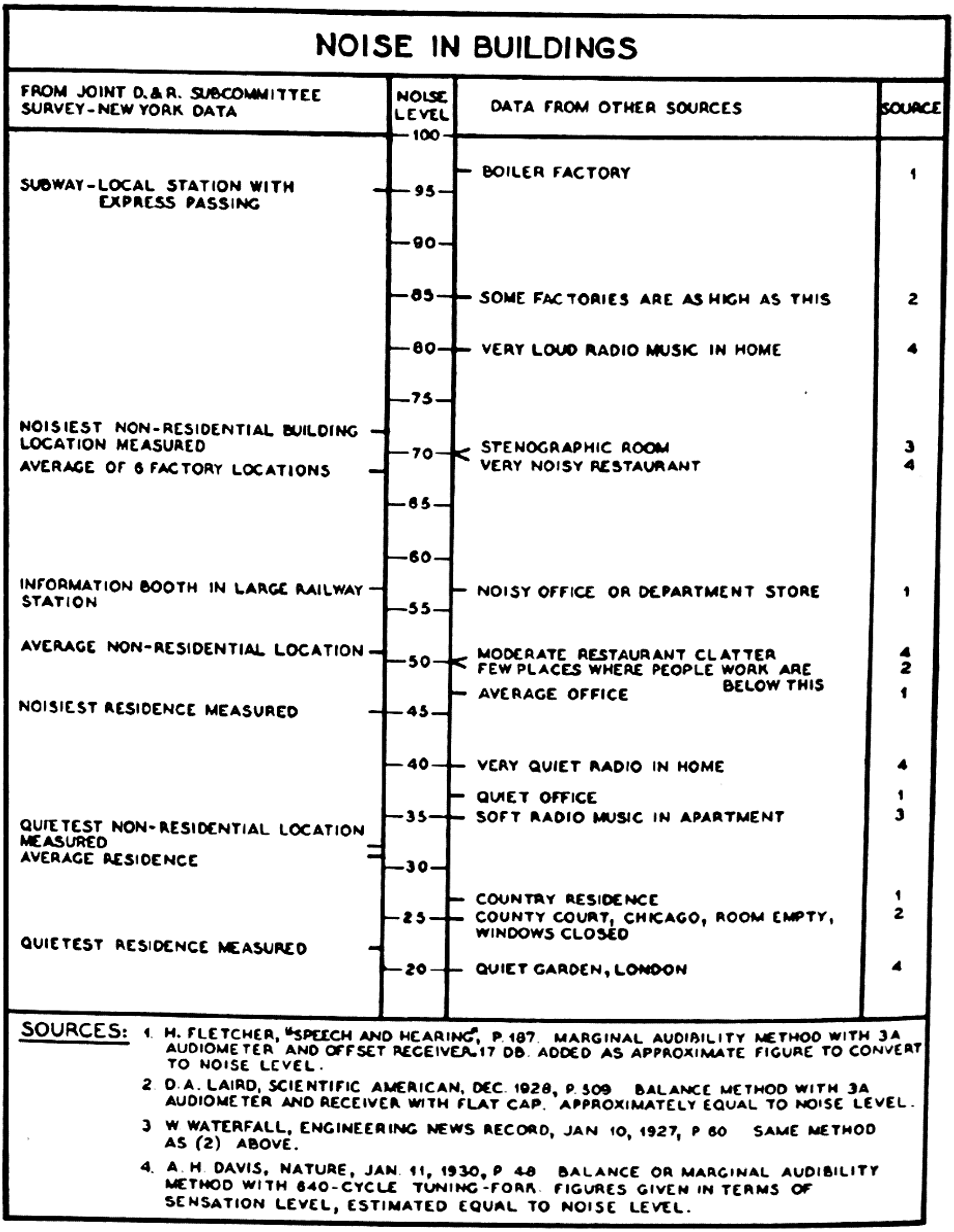
[2] Wallace Waterfall, *Technical Note,* No. 10a, The Celotex Company.

[3] K. C. Morrical, " Sound Insulation." *Architectural Record,* January, 1940, p. 73.

TABLE 15c

SOUND INSULATION DATA, FLOOR AND CEILING PARTITIONS

Description of Panel	Weight in Pounds per Square Foot	Cycles per second					Authority	Probable Average Value of T.L. in Decibels	Probable Average Value of r
		128	256	512	1024	2048			
		Reduction Factors in Decibels							
Airplane fabric, doped and varnished	0.055	....	3.6	3.0	5.9	10.1	Bureau of Standards	..	....
Fiber board, 0.5 in. thick	0.75	....	15.5	19.0	29.0	....	Davis and Littler	19	0.013
Hairfelt, 0.58 in.	0.58	....	6.2	6.1	6.3	....	" "	..	....
Birch veneer door, light, four panel	......	13.0	16.1	20.4	22.8	22.0	P.E. Sabine	22	0.0063
Oak, solid, 1¾ in., with cracks as ordinarily hung	......	11.5	15.1	20.4	22.0	16.2	"	20	0.01
Steel, solid ¼ in.	......	25.1	26.7	31.1	36.4	31.5	"	35	0.00032
Glass, ⅛ in., twelve panels	......	16.9	18.3	21.5	25.8	23.6	"	25	0.0032
Brick panel, Mississippi, 8 in.; plastered both sides gypsum brown coat, smooth white finish; good workmanship	0.87	....	50.2	47.6	55.5	63.5	Bureau of Standards	50	0.000010
Tile, clay, three-cell 3 in. by 12 in. by 12 in., plastered both sides gypsum scratch coat, very thin smooth-finish coat	......	....	39.1	....	35.7	59.3	"	41	0.000080
Wood studs, four-paper plaster board, three-coat smooth finish gypsum plaster	......	....	52.1	....	52.3	57.0	"	50	0.000010
Wood studs, metal lath, scratch and brown coats plaster (1 part sand to 1 part gypsum wood-fibered plaster)	......	....	43.4	....	43.7	55.0	"	44	0.000040
Concrete flat slab floor construction, reinforced. Floating floor consisting of nailing strips, rough and finish flooring. Insulite furred out and applied as ceiling	58.1	58.9	57.0	55.4	67.6	65.2	"	57	0.0000020
Tile, three-cell partition, 4 in. by 12 in. by 12 in. Ceiling finished with furring strips, ½ in. Insulite plaster	69.8	56.5	56.6	55.8	57.7	58.8	"	53	0.0000050
Wood joists. Lower side plastered on wood lath; upper side, subflooring and ⅜-in. finish flooring	......	47.9	46.8	40.7	50.1	48.8	"	43	0.000050



NOISE IN BUILDINGS

FROM JOINT D.&R. SUBCOMMITTEE SURVEY-NEW YORK DATA	NOISE LEVEL	DATA FROM OTHER SOURCES	SOURCE
	100		
		BOILER FACTORY	1
SUBWAY-LOCAL STATION WITH EXPRESS PASSING	95		
	90		
	85	SOME FACTORIES ARE AS HIGH AS THIS	2
	80	VERY LOUD RADIO MUSIC IN HOME	4
	75		
NOISIEST NON-RESIDENTIAL BUILDING LOCATION MEASURED			
	70	STENOGRAPHIC ROOM VERY NOISY RESTAURANT	3 4
AVERAGE OF 6 FACTORY LOCATIONS			
	65		
	60		
INFORMATION BOOTH IN LARGE RAILWAY STATION		NOISY OFFICE OR DEPARTMENT STORE	1
	55		
AVERAGE NON-RESIDENTIAL LOCATION	50	MODERATE RESTAURANT CLATTER FEW PLACES WHERE PEOPLE WORK ARE BELOW THIS	4 2
		AVERAGE OFFICE	1
NOISIEST RESIDENCE MEASURED	45		
	40	VERY QUIET RADIO IN HOME	4
		QUIET OFFICE	1
	35	SOFT RADIO MUSIC IN APARTMENT	3
QUIETEST NON-RESIDENTIAL LOCATION MEASURED			
AVERAGE RESIDENCE			
	30		
		COUNTRY RESIDENCE	1
	25	COUNTY COURT, CHICAGO, ROOM EMPTY, WINDOWS CLOSED	2
QUIETEST RESIDENCE MEASURED			
	20	QUIET GARDEN, LONDON	4

SOURCES:

1. H. FLETCHER, "SPEECH AND HEARING", P. 187. MARGINAL AUDIBILITY METHOD WITH 3A AUDIOMETER AND OFFSET RECEIVER. 17 DB. ADDED AS APPROXIMATE FIGURE TO CONVERT TO NOISE LEVEL.
2. D. A. LAIRD, SCIENTIFIC AMERICAN, DEC. 1928, P. 509. BALANCE METHOD WITH 3A AUDIOMETER AND RECEIVER WITH FLAT CAP. APPROXIMATELY EQUAL TO NOISE LEVEL.
3. W. WATERFALL, ENGINEERING NEWS RECORD, JAN 10, 1927, P 60. SAME METHOD AS (2) ABOVE.
4. A. H. DAVIS, NATURE, JAN. 11, 1930, P 48. BALANCE OR MARGINAL AUDIBILITY METHOD WITH 640-CYCLE TUNING-FORK. FIGURES GIVEN IN TERMS OF SENSATION LEVEL, ESTIMATED EQUAL TO NOISE LEVEL.

FIG. 15*d*. Decibel scale of noise levels in buildings. (Tucker, *Jour. Acous. Soc. Amer.*, Vol 2, p. 63, 1930.)

the matter of competing sounds, called "masking," whereby noise is not so noticeable as without the masking sound. For example, a person playing a piano in a room will not notice other sounds that would be annoying if he were reading. In this connection, Knudsen[1] lists the approximate magnitude of noises which will be accepted without complaint in different types of rooms and buildings.

Location	Maximum Noise Level Which Should Be Tolerated
	Decibels
Studios for the recording of sound (talking picture studios)	6 to 8
Radio broadcasting studios	8 to 10
Hospitals	8 to 12
Music studios	10 to 15
Apartments, hotels, and homes	10 to 20
Theaters, churches, auditoriums, classrooms, and libraries	12 to 24
Talking-picture theaters	15 to 25
Private offices	20 to 30
Public offices, banking rooms, etc.	25 to 40

Along with these values, the sound levels of common sounds in Fig. 15*d* should be consulted.

Conclusion. The preceding discussions indicate the important properties of constructions in the insulation of sound. While the matter seems rather complicated, is has been found that an intelligent consideration of the principles stated will bring the expected results. It should be remembered that the amount of vibration needed to produce sound is very small, and that the ear is extremely sensitive, even to faint sounds.

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[1] *Architectural Acoustics*, p. 330.

CHAPTER XVI

VIBRATIONS AND THEIR CONTROL

Sources of Vibration. One of the chief sources of acoustic disturbance in buildings is found in vibrations of some sort. These vibrations may be set up inside the building by motors, pumps, and other machines, or they may originate outside with trucks, street cars, and railway trains. In any case they get into the building structure and cause a disturbance for the occupants by mechanical vibrations of the floor or by annoying sounds set up by vibrating partitions and furniture, by rattling of windows, transoms, and other loose connections. The continuance of these nuisances throughout the day affects the efficiency of people attempting to work in the building. In factories, the floor vibrations may become so marked as to interfere with the ability of employees to perform their duties properly.

Extent of Vibrations. In buildings it has been found that vibrations occur in three directions, two horizontal and one vertical, these being due to machines, street traffic, and other causes. The magnitude of the vibrations is generally small, varying from about 0.0014 to 0.00004 inch; but it is likely that vibrations of factory floors exceed these values. The frequencies of the vibration vary from about 2 to 9 per second.[1] Vibrations of walls are capable of producing sound waves in the surrounding air that will be audible if the amplitude of vibration is large enough. There appear to be no data for this particular case, but some idea of the action may be gained from experiments by Shaw,[2] who found that a telephone receiver membrane vibrating with small double amplitudes gave sounds when held to the ear as indicated in the following table.

SOUNDS PRODUCED BY A VIBRATING TELEPHONE MEMBRANE

Double Amplitude	*Result*
0.000006 inch	Sound "just audible"
0.0004 inch	Sound "just comfortably loud"
0.008 inch	Sound "just uncomfortably loud"
0.04 inch	Sound "just overpowering"

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[1] E. E. Hall, "Graphical Analysis of Building Vibrations," *Electric World*, Dec. 18, 1915.

[2] *Proc. Royal Society of London*, Vol. 76A, p. 360, 1905.

Hall's values for building vibrations lie within these limits, but the sounds produced in air would be considerably fainter because they are not conveyed so directly or so efficiently to the ear as in Shaw's experiment. Information regarding the vibrations due to street traffic has been obtained by the U. S. Bureau of Public Roads.[1] A new instrument was devised which measures with scientific precision the effect of every shock and blow delivered by moving vehicles in crossing a bridge. The results show that a rapidly moving motor truck may strike a blow equivalent to seven times its actual weight. It is easily understood, from this illustration, why buildings are shaken by passing vehicles, particularly in the winter time when the ground is frozen and a more intimate contact is therefore made between the street and adjacent structures.

Methods for Minimizing Vibrations. In attempting to control the vibrations in buildings, two possibilities should be considered. First, it is obviously advantageous to reduce vibrations at the source, and second, it is then necessary to devise methods to hinder the progress of any disturbances that are not stopped at the source.

(*a*) *Reduction of Vibrations at the Source.* A systematic study of the problem of unbalanced machines has led to practical means of correcting these defects so as to secure a smooth-running mechanism with a minimum of vibration. It is necessary to secure not only a statical equilibrium but also a dynamical balance when the machine operates. This result is accomplished for stationary machines by reducing the weight of certain sections of the rotating parts, as indicated by the theory and by measurements taken with balancing instruments. The noises of street traffic have been reduced by various means, for example, the substitution of busses for streetcars and of automobiles for horse-drawn carriages, and the use of rubber-tired wheels for milk wagons. A study of the great disturbance caused by elevated roads led the engineers of the Department of City Transit, in Philadelphia, to build a road incorporating constructions intended to minimize vibrations and noise.[2]

The objects sought for in the elevated structure were "rigidity at all times; solidly built bridge work with vibrations minimized, and rigid trains with no free play at the couplings for the usual jolting during starting and stopping." Attention was paid also to the car noises. A special type of gearing was used between the motor and the car wheels that greatly reduced the usual disturbance. The cars were constructed with tight-fitting parts to prevent rattling. Subway cars have been redesigned to create less noise. The chief features of these new cars are faster starting and stopping, rubber cushioning in springs and wheels to reduce noise and shock, greater length and width than in present cars, reduced weight, and streamlining.

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[1] "Impact on Bridges," *Science*, Vol. 54, p. 625, 1922.

[2] "The Noiseless Elevated," by Wm. A. McGarry, *Scientific American*, Vol. 126, pp. 46–47, January, 1922.

Other sources of reductions might be mentioned, such as the use of improved roadbeds of concrete to promote smooth running for autos; wood and rubber block pavement to deaden noises of wagons and horses. In buildings, disturbances are lessened by quiet elevator service, slow-velocity fans for ventilation, and large pipes for plumbing to give a slower flow of water for both tubs and toilets.

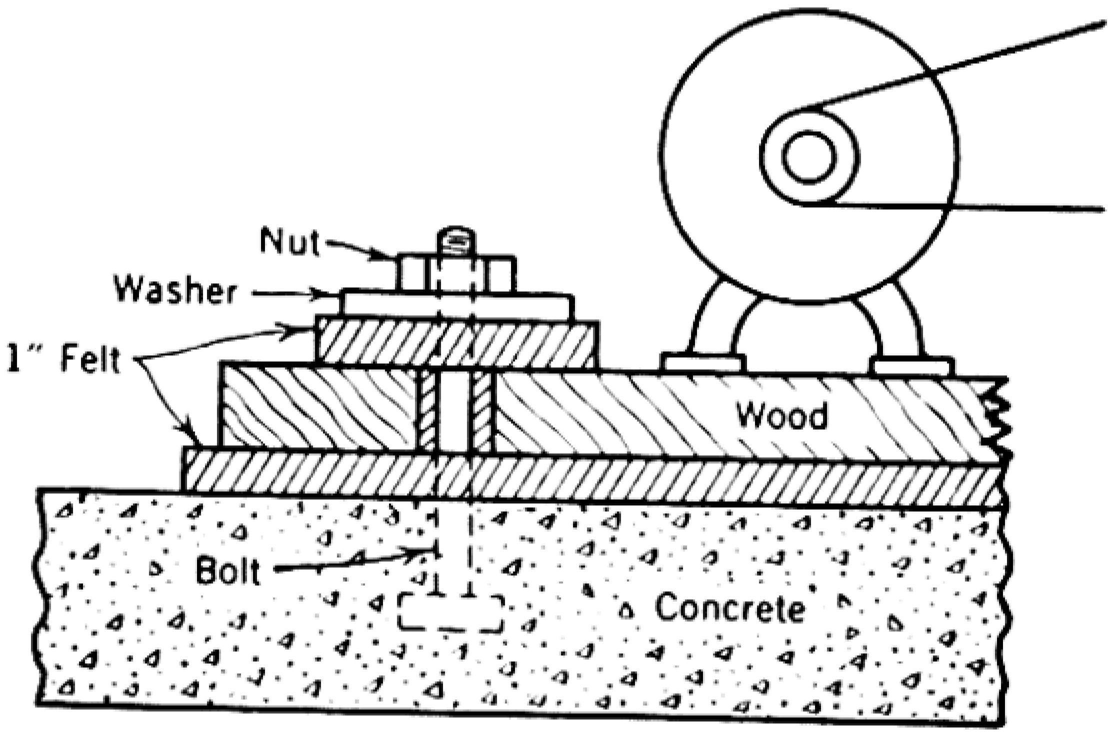

FIG. 16*a*. Diagram of construction for attaching machine footing to building structure so as to minimize vibrations. (F. R. Watson.)

(*b*) *Control of Vibrational Waves.* The second large problem in the reduction of vibrations is to stop the vibration waves that progress from the source. The effective method is to interpose a discontinuity of some sort that hinders the passage of the vibrations. For instance, heavy machinery in buildings should be located in the basement, if possible, and insulated from the surrounding structure by being mounted on a heavy base floated on crushed rock and separated from the main floor by a small gap filled with asphaltum or rubber. Where it is necessary to mount machinery in the upper parts of buildings, as rigid a support as possible should be sought, and the machine base should be insulated by a special arrangement of flax, felt, etc., as shown in Fig. 16*a*. Vibrations generated outside a building may be partly insulated by the same procedure. If a roadbed were floated on crushed rock, the vibrations from passing trucks and street cars would be hindered in their passage. Insulating the foundation walls of a building by suitably compacted crushed-rock bases or similar structures should minimize the transmission of vibrations from the street.

Insulation of Machines. The insulation of machine vibrations is not a simple matter. There is a prevailing, incorrect idea that such vibrations will be controlled if a sheet of cork is placed under the machine. Usually this procedure makes the vibrations more vigorous; the insulating material should " give " somewhat under the weight to be effective. Theory, supported by extensive practical applications, indicates that an elastic support for the machine will reduce vibrations, but the support should be designed intelligently. These supports may be divided into two classes: first, those that are intended to produce insulation from shocks and from disturbances of unpredictable (low) frequency, which should have considerable *damping;* second, those designed to produce insulation from disturbing sources of known, constant (high) frequency, which should be *elastic with small damping*. The theory for the control of vibrations is too extensive for the purpose of this book, but the following simple examples will illustrate the procedure of application.

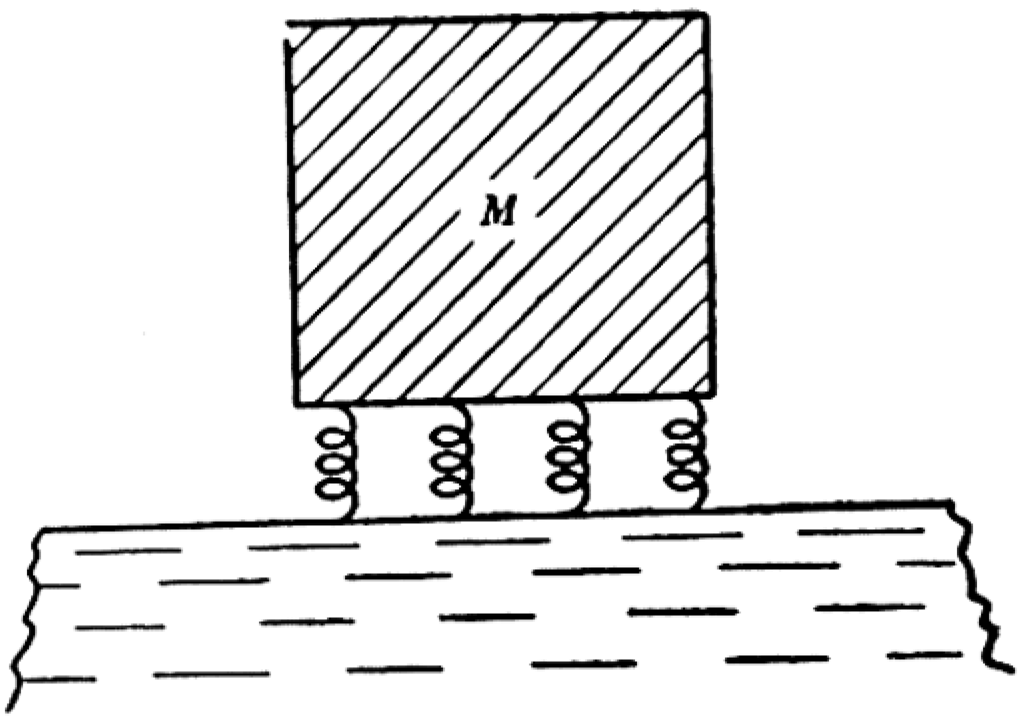

FIG. 16*b*. Machine insulated by elastic springs.

Theory of Insulation. Consider a machine (not running) of mass M resting on springs that " give " somewhat under the load, and that when set in motion will oscillate up and down with a frequency ω_1. Suppose further that, when the machine is running, it sets up an oscillating vertical force of frequency ω. For these conditions, it is shown that the ratio, ϵ, of the maximum force transmitted vertically to the floor to the maximum vertical force set up by the machine is given by the equation

$$\epsilon = \sqrt{\frac{b^2\omega^2 + M^2\omega_1^4}{b^2\omega^2 + M^2(\omega_1^2 - \omega^2)^2}} \qquad \text{(A)}$$

where b is a friction factor. Friction and phase difference being neglected, this equation reduces to:[1]

$$\epsilon = \frac{1}{(\omega/\omega_1)^2 - 1} \qquad \text{(B)}$$

As an example, suppose the frequency ω of the machine to be 1800 rpm or 30 rps (30 cycles per second), and the frequency of motion ω_1 of the machine (not running) on the springs to be 7.5 cycles per second; then:

$$\epsilon = \frac{1}{(30/7.5)^2 - 1} = \frac{1}{15}$$

This result means that the maximum force exerted vertically on the floor is only $\frac{1}{15}$ of the maximum vertical force set up by the running machine.

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[1] E. H. Hull, "Influence of Damping in the Elastic Mounting of Vibrating Machines," *Amer. Soc. Mech. Eng. Trans.*, Vol. 53, p. 155, 1931.

Figure 16c shows the result graphically. Several cases should be considered.

1. For $\omega/\omega_1 = 0$, meaning that the machine is not running, or is running very slowly, so that $\omega = 0$, the value of $\epsilon = 1$. The maximum vertical force on the floor is then equal to the maximum vertical force set up by the machine.
2. For $\omega/\omega_1 = 1$, ϵ becomes infinite according to equation B, indicating a resonant vibration. However, since there is always some friction, there is never an infinite amplification of the force, and equation A shows how the friction reduces ϵ, the larger the friction, the smaller is the amplification.
3. For $\omega = \omega_1\sqrt{2}/2$, $\epsilon = 1$, for all values of the friction.
4. For ω/ω_1 greater than $\sqrt{2}/2$, the value of ϵ decreases and the force transmitted to the floor gets less and less compared with the force set up by the machine, which is a desirable reduction. For this case, the damping is detrimental, since the value of ϵ may be doubled for a certain value of the friction.

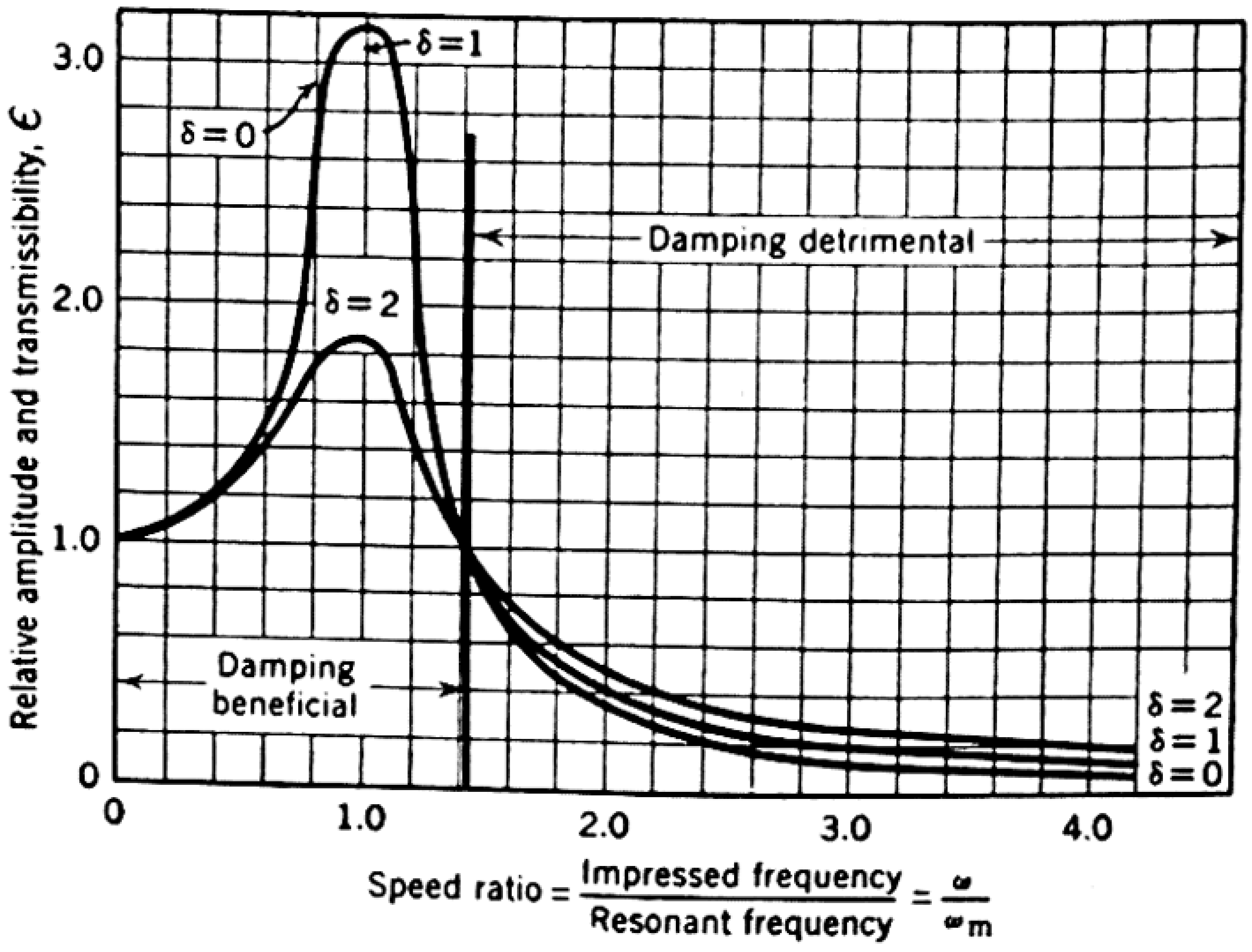

FIG. 16c. Curves showing theoretical results of insulation of machines. (Hull.)

Summary. As stated in the beginning, if the machine is running steadily with a known frequency greater than the frequency of the arrangement with the machine not running, it can be " insulated " from the floor by elastic springs, assuming small damping. If, however, the frequency of the machine is small, or if the machine exerts sudden, low-frequency shocks, a damping insulator will be more efficient. Further information about this important, extensive subject is left to the reader.[1]

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[1] Timoshenko, *Vibration Problems in Engineering*. J. P. den Hartog, *Mechanical Vibrations*. Slocum, *Noise and Vibration Engineering*.

CHAPTER XVII

EXAMPLES OF SOUNDPROOFING

Introduction. The problem of sound insulation of walls and partitions in buildings has demanded considerable attention, but a lack of practical and readily available data, as well as an abundance of misinformation and guesswork, has hindered success in finding satisfactory solutions. Chapters XV and XVI indicate the progress that has been made in recent years in obtaining reliable results for the sound-deadening values of partitions and the reduction of vibrations. This chapter is devoted to descriptions of practical utilizations of existing theories and data.

Soundproof Rooms. The conditions that control sound insulation in rooms have been discussed in Chapter XV. Generally a room should have continuous walls with tightly closing doors and windows, with ventilating ducts properly deadened, and with sound-absorbing materials to reduce any objectionable reverberation. If some attention is paid to these details, offices, hotel rooms, and hospital rooms can be made sufficiently soundproof for usual purposes with standard building constructions. When greater insulation is desired, it will be necessary to use special devices for which information can be found in Chapters XV and XVI, and in the references given there.

Insulation of a Doctor's Office. An interesting and surprising example of sound insulation is illustrated in Fig. 17*a*, which shows a doctor's office and the waiting room adjacent to it. Patients coming into the doctor's office from the waiting room asked if their conference could be conducted quietly, stating: " We could hear the conversation between

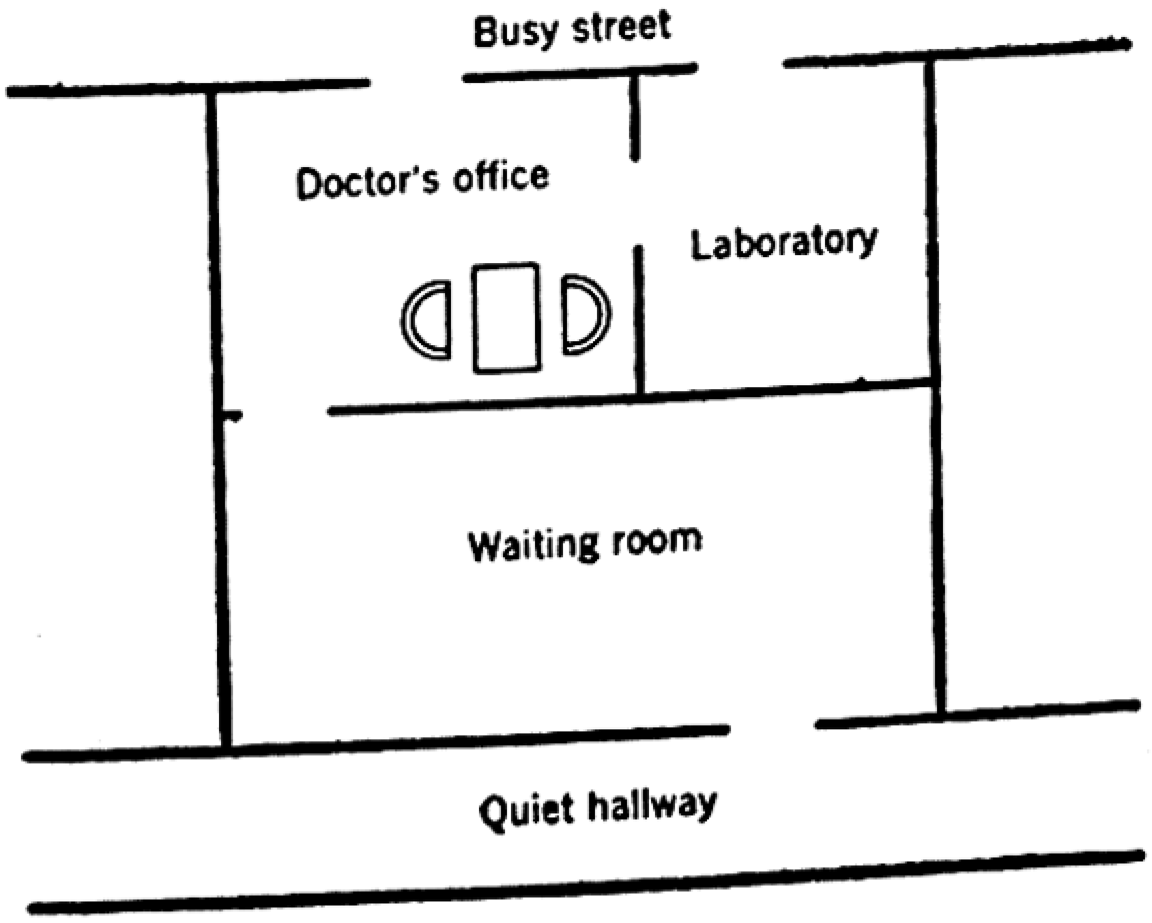

FIG. 17*a*. Diagram of doctor's office and waiting room. Patients in the waiting room could hear the conversation in the doctor's office. Extra insulation needed to correct the trouble.

you and patients that preceded us." This situation was disconcerting to the doctor, and surprising because the connecting door and dividing partition had received the usual amount of sound insulation. The explanation for this unusual sound transfer appears to be as follows. The noise of the street was so loud as it entered the doctor's office through the open windows that the doctor raised his voice to overcome it, thus creating a sound level of perhaps 75 db. Assuming that the door and partition were fairly efficient, with an insulating value of say, 35 db, the original sound would be reduced from 75 to 40 db, which could be heard easily in the quiet waiting room where the sound level was about 30 db, owing to the very quiet hallway. Installation of a more efficient sound-insulating door and an increase in the partition deadening eliminated the trouble.

Extremely Quiet Constant-Temperature Room. An extreme example of sound quieting is illustrated by a constant-temperature room, shown by the diagram in Fig. 17*b*. This room was designed primarily for magnetic measurement, requiring very small variations in temperature.

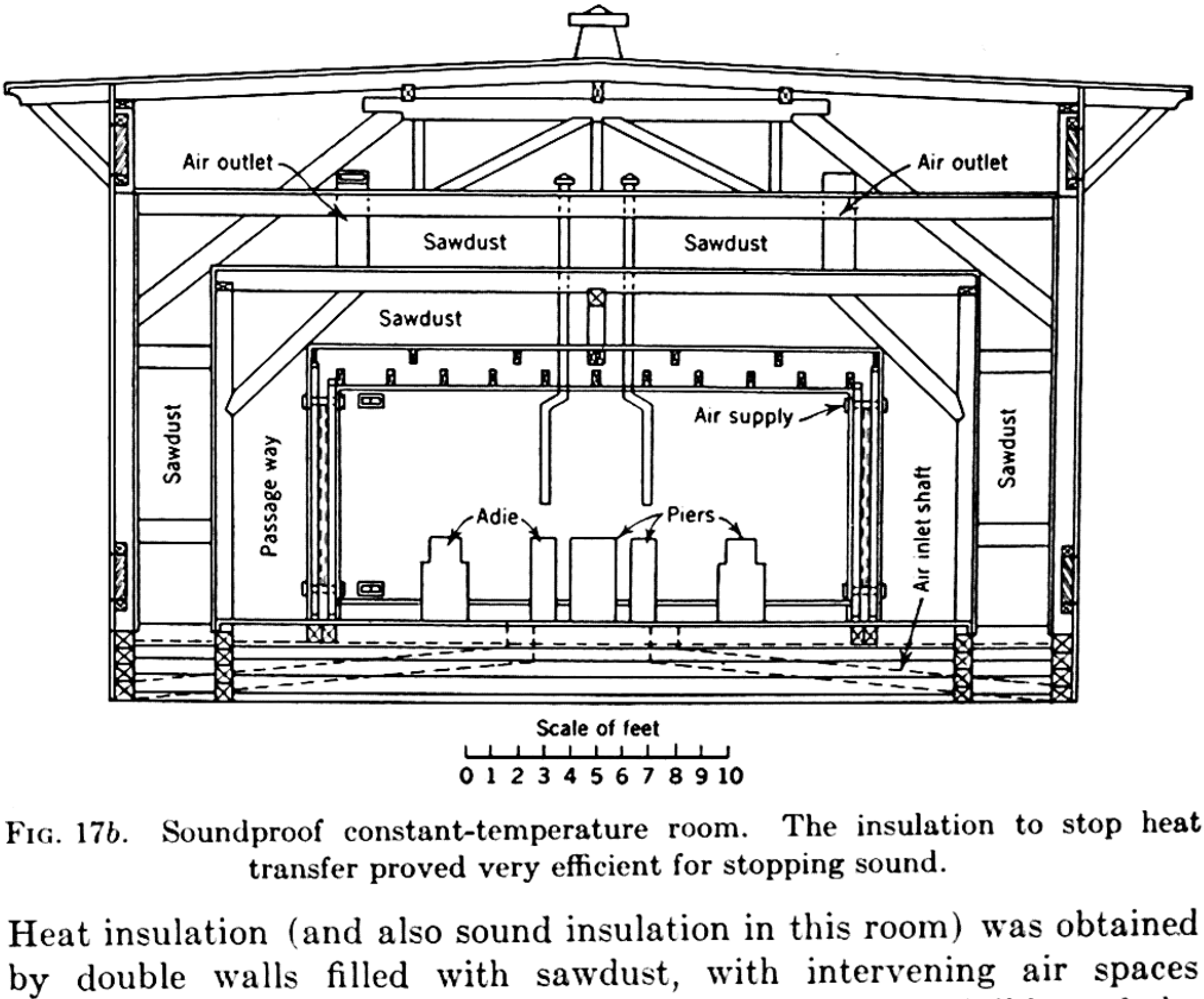

FIG. 17*b*. Soundproof constant-temperature room. The insulation to stop heat transfer proved very efficient for stopping sound.

Heat insulation (and also sound insulation in this room) was obtained by double walls filled with sawdust, with intervening air spaces (passageways). The daily temperature range was negligible and the annual range only a few degrees.

One of the observers stated that the room was so nearly soundproof that he thought he would be unable to make outsiders hear in case he were in distress, from lightning or other causes. Trial by shouting within the room gave almost no sound outside, and the faint sound that

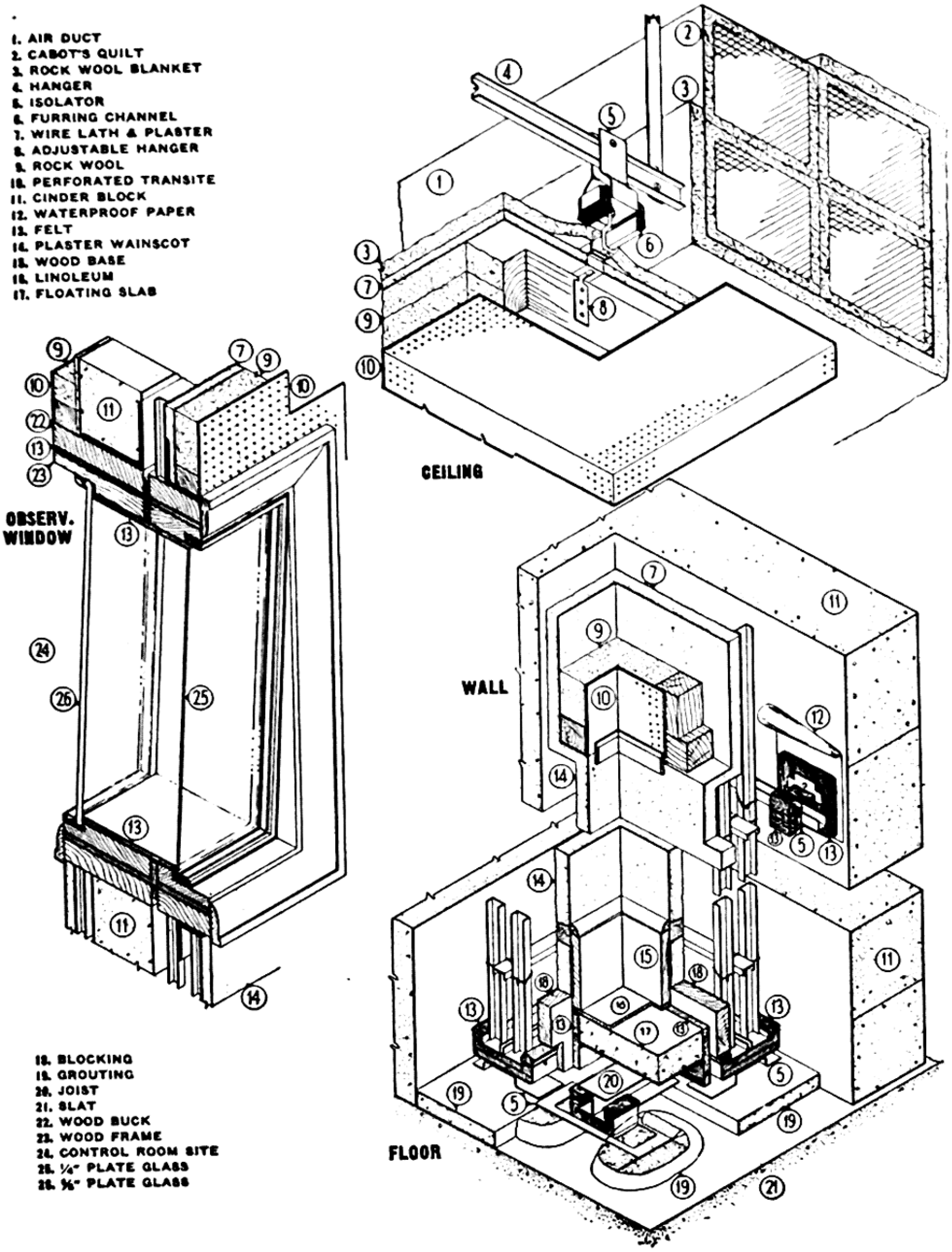

FIG. 17*c*. Details of sound-insulation constructions employed in the National Broadcasting Building in Hollywood. (O. B. Hanson, *Architectural Forum*, Vol. 70, p. 167, 1939.)

was perceptible appeared to be due to the passage of sound through the air ducts in the floor.[1]

Soundproofing a Building. The degree of soundproofing required in buildings depends on the purpose of the structure. It is becoming a more common practice to control sound in entire buildings, instead of in a few isolated offices and rooms; the contrast between the quieted rooms and the remaining untreated parts of the building is so noticeable as to arouse resentment by occupants of the noisy quarters.

In hospitals, as already stated, it is usually sufficient to install sound-absorbing materials on the ceilings of the corridors, with acoustic treatment for a few noisy rooms. In hotels, the carpets and furniture in the rooms appear adequate for quiet, and the carpet in the hallways deadens the noise of footsteps. The sounds of loud talking and laughing in the hallways, particularly objectionable late at night, can be reduced by tight-closing doors and transoms, assuming that ventilation is provided by some other arrangement.

Elevator disturbances may be minimized for hotel guests by grouping the elevators together and surrounding this space up through the hotel by stairways, storerooms, etc., so that the elevators are not immediately adjacent to hotel bedrooms.

In office buildings, it is desirable to apply acoustic treatment to ceilings of offices and corridors, with additional side-wall deadening in rooms in which machines are operated. Movable screens of sound-absorbing material placed near noisy calculating and tabulating machines are advisable.

Music buildings and especially buildings used for broadcasting require special study for adequate control of sound. Ventilation systems should have slow-velocity fans and a slow flow of air; the ventilation duct should be lined with sufficient duct-liner of a suitable type. Figure 17*c* shows the special devices employed to insulate sound in the National Broadcasting Company in Hollywood. These devices are repetitions or improvements of the effective means employed in Radio City, New York.

Machine Disturbances. Control of vibrations has already been discussed, showing the necessity of using elastic springs under the machines that " give " a calculated amount under the weight of the machine. Noises sent out into the *air* from the machine require a different treatment. For example, a brick-rattling machine used by the Highway Engineering Department at the University of Illinois, was extremely noisy and disturbed classes in the nearby buildings so much that suggestions for a method of minimizing the disturbance were requested. The machine was mounted on a platform and enclosed first in a sheet-iron covering which served to prevent the escape of dust as well as sound. See Fig. 17*d*. A larger, double-walled wooden box, having

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[1] " Results of Observations made at the Coast and Geodetic Survey Magnetic Observatory at Cheltenham, Maryland, 1901–1904," Dept. of Commerce and Labor, U. S. Coast and Geodetic Society, pp. 11–13, 1909.

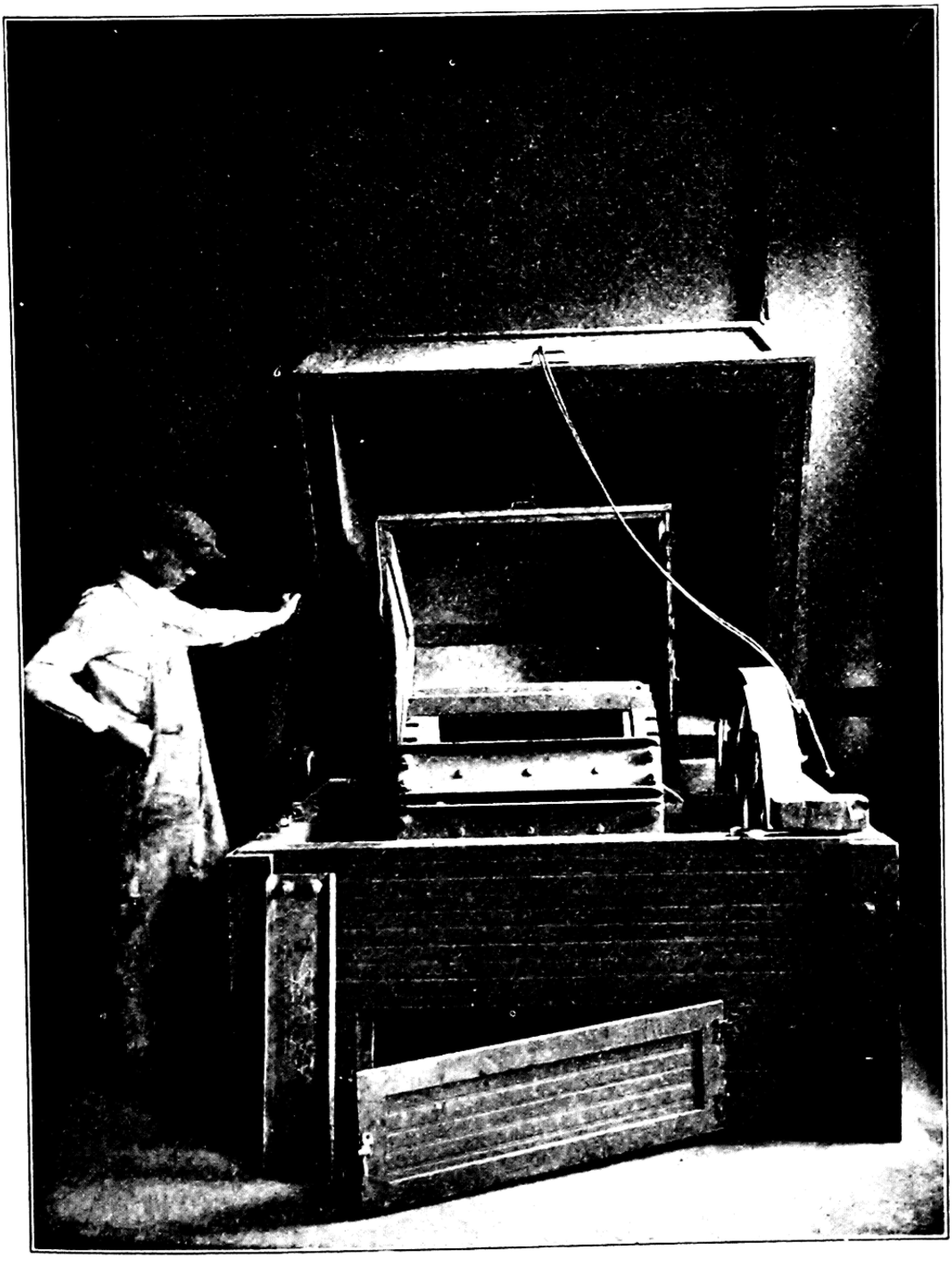

Fig. 17*d*. Soundproof box to reduce noise of brick rattler.

the interspace filled with sawdust, and equipped with a hinged cover, was built to give further insulation. Without the covers, the machine is so noisy, that one person cannot be heard by another without shouting loudly into his ear. With the covers on, the noise is greatly reduced and conversation is possible. This construction has economic value because, with noisy machines, the hearing, and therefore the efficiency, of employees becomes affected.

Buzzers. When attached intimately to walls, a buzzer creates two disturbances: it gives out the air-borne sound which it is supposed to produce, but it also sets up a disturbing vibration in the wall that travels through the solid structure to the adjoining rooms. Such vibrations can be reduced by interposing felt or soft rubber between the buzzer and the wall by an arrangement similar to the one shown in Fig. 16*a*, so as to break the solid connection.

Other Examples. Pianos may be insulated somewhat from the floor by a similar device. The castors of the piano can rest in glass " cups " devised for this purpose, with at least ½-inch-thick felt attached to the under side of the cups, if insulation is to be achieved. Carpets with thick lining act in the same manner to insulate footstep sounds from the floor, thus reducing the disturbance for occupants in the rooms below.

Ventilation Systems. Sound travels about as easy in ventilation ducts as it does through speaking tubes. Control of the transfer of sound is brought about by lining the ducts with special sound-absorbing materials. The best type of material and the amount needed should be specified by the commercial companies experienced in the installation of such treatment. It is necessary to know the nature and loudness of the ventilation and other sounds to be controlled, the conditions in the rooms into which the ventilation leads, and also the size and length of the ducts. The attenuation of sound (in decibels) in pipes and ducts depends directly on the length of the duct, is approximately proportional to the sound-absorbing efficiency of the inside lining, and (for circular pipes) is inversely proportional to the diameter of the pipe.[1] For rectangular ducts with all the interior walls covered with the same material, the attenuation is proportional to the ratio of the perimeter of the duct to its area of cross-section.[2]

Plumbing. Disturbing sounds are often caused by flow of water in pipes, as many hotel guests can testify. A slow-velocity flow gives a gratifying reduction in noise. Large pipes for bathtubs allow a generous flow of water with a barely perceptible noise, with consequent less annoyance to occupants of adjacent room. Toilets have been developed with a correspondingly quiet action.

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[1] *Technologic Papers of the Bureau of Standards,* No. 333, 1926.

[2] R. Rogers, *Jour. Acous. Soc. Amer.,* Vol. 11, p. 480, 1940.

Soundproof Doors. When effective insulation is desired, as in music buildings and broadcasting rooms, the use of soundproof doors is recommended. Doors have been developed that make a tight closure all around including the threshold cracks, and thus reduce sound some 10 to 20 db more than ordinary doors.

Partition Doors. In some buildings, it is desired to have an arrangement by which a large room may be divided temporarily into two small rooms. This is accomplished by means of a suitably designed folding partition that can be pulled out from one wall and fastened tightly to the opposite wall, or by two sections that extend out from the walls to be fastened in the center of the room. These partitions are not so effective as permanent partitions, giving only about 25-db reduction, but improvements are being investigated. (Modern-fold Doors, Newcastle Products Co., Newcastle, Indiana.)

Quieting Airplane-Engine Sounds. The noise of airplane engines being tested is extremely loud, becoming more than 100 db. During

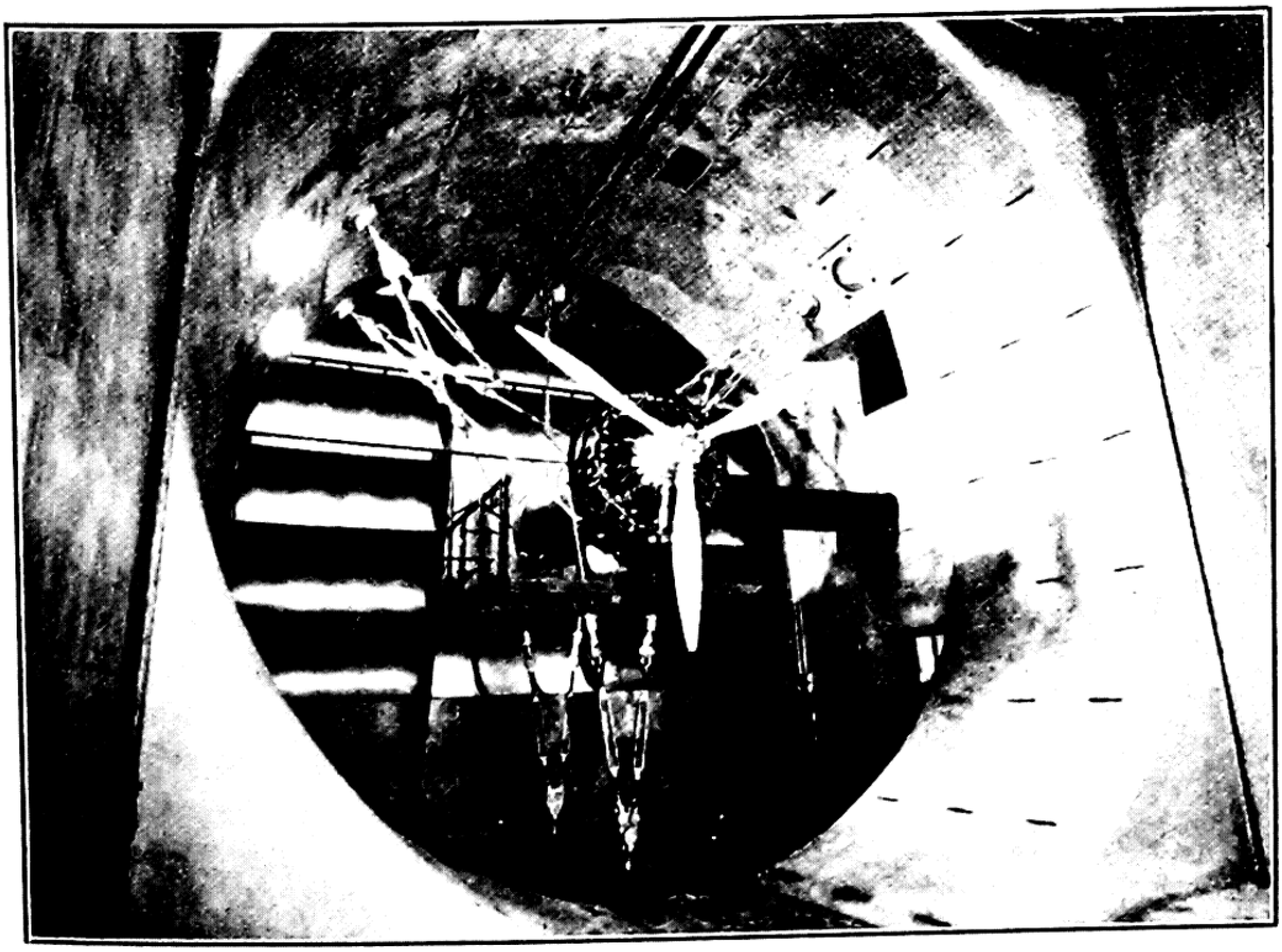

FIG. 17*e*. Testing chamber for airplane engines, lined with sound-absorbing material to reduce noise. (Pratt & Whitney Engine Test House, Hartford, Conn. Albert Kahn, Inc., Architects and Engineers. From *Architectural Forum*, August, 1938, p. 128, M. J. Brennan.)

these tests, the propellers create a vigorous current of air that is drawn into the building through various intakes and forced out through

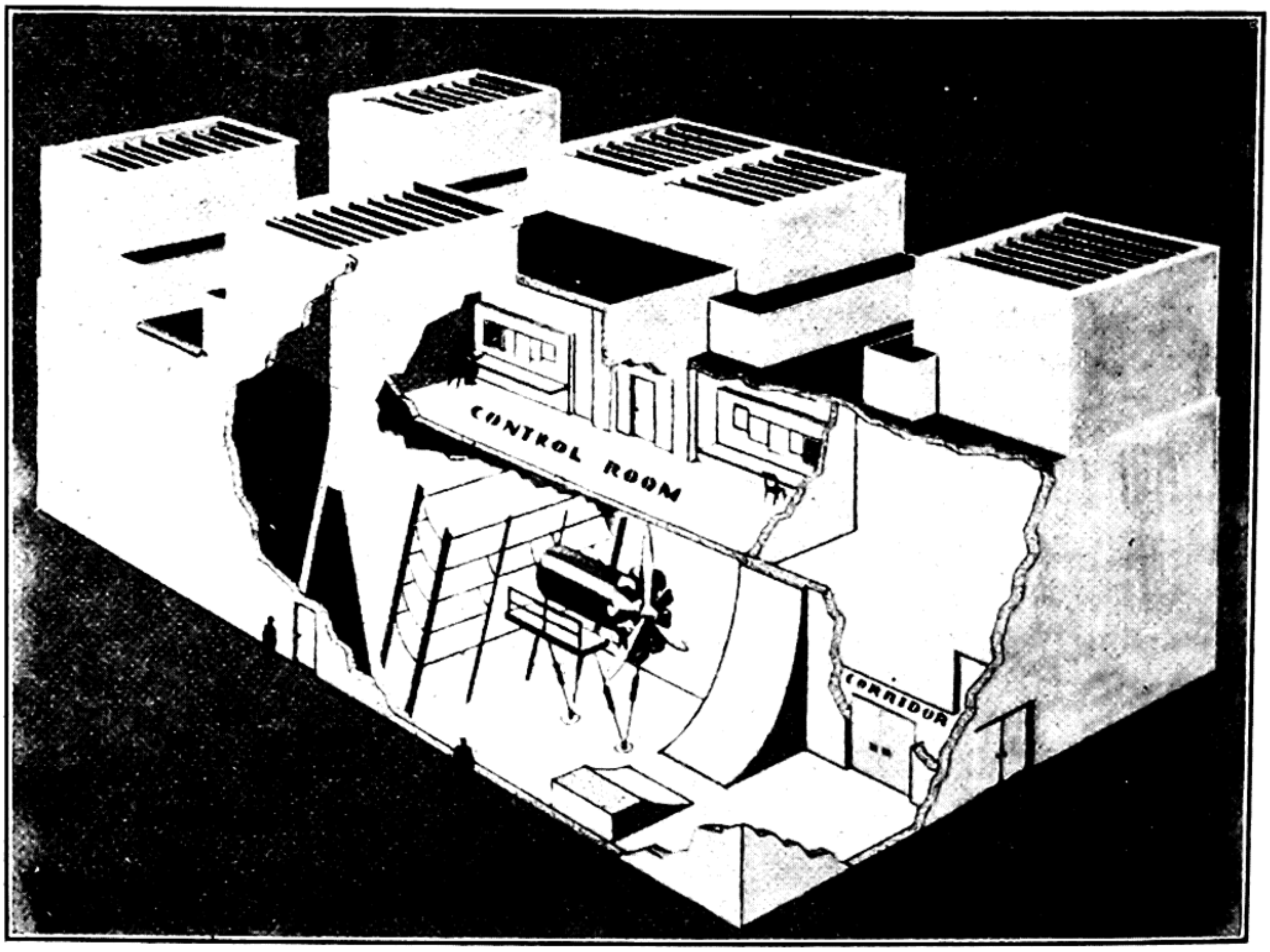

FIG. 17*f*. Isometric view of the building housing the test chamber of Fig. 17*e*.

exhausts. The noise generated is objectionable not only to the occupants of the building but also to the residents in the surrounding neighborhood. Unusual measures are necessary to reduce the sound. Figure 17*e* pictures an observation chamber in which the engine under test is suspended by a three-way insulated support to reduce vibrations reaching the walls. The noise in the room is reduced somewhat by sound-absorbing tile on the interior surfaces. To minimize noise on the outside, a sound-absorbing tile, Calistone, was suspended in parallel rows within the stacks to reduce escaping sound, and exterior walls of 18-inch reinforced concrete were constructed to reduce the vibrations produced by the engines. Figure 17*f* gives an isometric view of the building.

Noise in Burglary-Resistive Vaults. An interesting investigation was conducted by the Underwriter's Laboratories, Inc., to ascertain the noise condition in burglary-resistive vaults to obtain data to be used as guidance in specifying requirements for burglar alarm systems.[1]

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[1] H. D. Brailsford, *Bulletin of Research*, No. 17, July, 1940, 75 pages.

Table 17*a* reproduces a sample set of data taken from the extensive results published. A sound-level meter was used to measure the sound inside the vaults and also in the lobby outside; the difference in readings was taken to give an approximate indication of the attenuation of sound in passing through the walls of the vault. For specifying protective devices, it appears necessary to have data on the sound produced by burglarious attacks by mechanical methods and by oxyacetylene torches in reverberant and dead rooms, as well as the sound-insulation efficiency of the walls.

TABLE 17*a*

NOISE LEVELS IN BURGLARY-RESISTIVE VAULTS

Construction	Wall Thickness, inches	Free Volume, cubic feet	Reverberation, Time, seconds	Lobby Noise Level, db	Vault Noise Level, phons	Vault Sound Energy Level, db
Concrete	18	1,066	6.65	48–62*	36†	37
Air space	1					
Steel	½					

* Bookkeeping machine.

† Clock on alarm system.

Quiet Streetcars. The Clark Equipment Company of Battle Creek, Michigan, has developed a new type of car, with devices based on the general principles of reduction of vibrations that practically eliminate the noisy elements of the old cars. Gear noise, which was the loudest and most objectionable disturbance in the old streetcars, almost disappears with the use of the new-type hypoid gears, recently adopted in all automobile drives. The solid steel wheels which pounded the rails and rail joints and created a terrific noise are replaced by new wheels of revolutionary design. These new wheels have rubber cushion " sandwiches " 20 inches in diameter and 1½ inches thick, that insulate the steel tire that runs on the rail from the wheel hub, thus not only reducing the noise common to steel wheels, but also preventing shocks from being transmitted up into the car. Instead of noisy brake shoes and brake rigging, special brake drums are mounted on the end of the electric motor shafts with a composition facing similar to the brakes on automobiles, thus giving a smooth, velvety application without noise. The body of the car is supported on sixteen rubber springs without any metal contact between the car body and the trucks. These not only absorb vertical shocks, but also have resilience in other directions, being based on the shear principle of rubber loading. The features just discussed, and others, have resulted in the creation of a new car with practically all the noise of the older type of cars eliminated.[1]

New " Pendulum " Suspension Railway Cars. In the conventional railroad-truck construction, the springs supporting the car are located at a considerable distance below the center of gravity of the car, with an instability in the form of objectionable and even dangerous roll that results from the use of soft springs. The fundamental scheme in the new car is to support the car above the center of gravity in a manner which is inherently stable, and which allows all necessary vertical and lateral movement against soft-spring restraints. The wheels follow the rail irregularities while the car body floats smoothly about a central position. This arrangement illustrates the insulating value of springs as explained in Chapter XV.

Imagine a set of four stout spiral springs, mounted near the center of each of the two trucks of the car and extending upward several feet. The car body rests on the tops of these springs by means of horizontal shelves near the roof of the car, so that the main body of the structure hangs below the points of suspension, and thus has freedom for a modified pendulum action. The four springs are arranged two on each side of the passageway of the car, so as not to interfere with the movements of passengers. The springs carry only vertical load and allow, within limits of safe stress, sufficient horizontal movement relative to the bottom for all lateral and turning movements of the truck. Lateral movements of the car body floating on the main springs are restrained by control arms and links which act on the body above the center of gravity. The control arms mounted in rubber give a variable spring rate for lateral motion, so that the car floats about a central position with small restraint.

Experimental cars have been tested on the Santa Fe Railroad in Southern California, up to speeds of 100 miles per hour. In direct comparison with standard cars on the same train, these new cars show much greater stability and comfort in riding. These test cars are light in weight and streamlined. Further experiments are in progress.[2]

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[1] A. O. Williams, *New York Railroad Club Proceedings*, November, 1939.

[2] " A Fundamental Development in Suspension and Construction for Railway Cars," by P. K. Beemer, F. C. Lindvall, E. F. Stoner, and W. E. Van Dorn, *Mechanical Engineering*, November, 1940, pp. 779–784.

PROBLEMS

CHAPTER I

ORIGIN AND PROPAGATION OF SOUND

1. Draw diagram showing how a tuning fork sets up sound waves. Show a complete wave including a compression and rarefaction.

2. Recalling that each air particle in a sound wave executes a simple harmonic motion similar to that of the bob of a pendulum making a small arc, describe the motion of such a particle during one complete cycle. Draw the particles for a complete wave, showing the relative displacements and velocities of the various particles.

3. What do you think the effect would be when a series of sound compressions and rarefactions traveling in the air is incident on a window pane or a thin partition?

4. A tuning fork makes 1,000 complete vibrations per second. How long a time is taken to complete a compression? (*Ans.* 0.0005 sec.) A rarefaction? How far will a compression travel in air in the time for the fork to make one complete vibration? (*Ans.* 1.12 ft.) What is this distance called? How far will a compression travel in 1 second? Velocity of sound is 1,120 ft/sec.

VELOCITY OF SOUND

1. The velocity of sound in a medium is given by the formula: $V = \sqrt{E/d}$, where E is the elasticity and d is the density. Calculate the velocity of sound in steel, for which $E = 22 \times 10^{11}$; $d = 7.5$. (*Ans.* 540,000 cm/sec, or 17,700 ft/sec.)

2. The velocity of sound increases about 1.1 ft/sec for each degree Fahrenheit rise in temperature. Taking the velocity of sound as 1,090 ft/sec at 32°F., calculate the velocity at 72°F. Can you imagine the disturbing effect on the regular progress of sound in a room that has a ventilating system with irregular currents of hot and cold air?

3. A workman at one end of a suspension bridge 6,600 ft long hits a steel cable with a hammer, while a second workman listens at the other end of the bridge. Calculate the time difference between the arrival of the sound through the cable and through the air as observed by the second workman. (*Ans.* 5.52 sec.)

REFLECTION OF SOUND

1. An observer stands on a floor where he is located at the center of curvature of the curved ceiling. Why does he get a sharp echo when he claps his hands? Draw a diagram showing the path of the sound rays, taking the radius of curvature of the ceiling as 60 ft.

2. Suppose that the observer in problem 1 moves sideways until he is 75 ft from the center of the curved ceiling. Where is the sound focused? (The solution can be made graphically by remembering that the angle of incidence of the rays equals

the angle of reflection, as in Figs. 1*c* and 1*d*.) Find the solution numerically by calculation from the equation: $1/p + 1/q = 2/r$, where p and q are the respective distances from the center of the curved ceiling to the source of sound and the focusing point of the reflected sound, and r is the radius of curvature of the ceiling. (*Ans.* $q = 50$ ft.)

3. Draw diagram of the reflected sound as in problem 1, but with the curvature of the ceiling reversed.

4. Consider a " barrel-vault " ceiling, i.e., one that is part of a hollow cylinder. In this case, the sound from the ceiling is not reflected at a point, as in problem 1, but is focused along a line. As an example, using the equation in problem 2, calculate the focusing point for each of the following cases, taking the radius of the ceiling as 60 ft, and the source of sound 60 ft vertically below the center line of the ceiling:

(*a*) Sound passing vertically upward.
(*Ans.* 60 ft, at the same point as the source.)
(*b*) Sound passing obliquely 75 ft from source to center line of ceiling.
(*Ans.* Focus 50 ft from point where sound strikes the ceiling.)
(*c*) Sound passing 90 ft from source to center line of ceiling.
(*d*) How would you alter this barrel-vault ceiling for better acoustics?

INTERFERENCE OF SOUND

1. Under what circumstances will two sets of sound waves reinforce each other? Tend to annul each other? How are standing waves set up?

2. If a small organ pipe giving about 2,000 cycles per second is sounded in a lecture room, the students in the seats can observe " loud spots " by simply moving their heads about. Explain. What difference would be expected if a pipe giving 500 cycles per second were sounded in the room?

3. What are " beats " in sound? Two motors, designed to run at 1,200 rpm, fluctuate in speed somewhat and set up beat sounds. What difference in the rates of revolutions will give 2 beats per second? (*Ans.* 120 rpm.)

DIFFRACTION OF SOUND

1. Why does a fish line in the water have but little effect on the water waves?

2. An observer finds that the loud sounds of his voice are reflected from a grove of trees near by. Why would reflection and diffraction from the leaves on the trees explain this action?

3. A boy claps his hands in front of a public building and hears a musical sound reflected and diffracted from the steps. Calculate the frequency of the reflected sound if the steps are 1 ft wide. Take velocity of sound as 1,120 feet/sec.
(*Ans.* 560 cycles/sec.)

4. Sound waves with a wavelength of 1 ft strike perpendicularly at a coffered ceiling. Draw diagram giving compressions and rarefactions to show that the depth of the coffers should be 3 in. if the sounds reflected and diffracted from the bottom of the coffers and from the spaces about the coffers are to interfere effectively.

5. If a person sits near the axis line of a distant conical megaphone, why is it that he hears all the sounds of both high and low frequency, but if he is located some distance sideways from the axis, he hears only the low-frequency sounds?

6. What approximate width should absorbing strips installed on a wall have if they are to diffract sound of 500-cycle frequency effectively, as in Fig. 1*i*. (*Ans*. One wavelength, or less.)

MUSICAL SOUNDS

1. Draw two simple sound waves, and plot their resultant by adding the amplitudes of the waves, so as to give the center figure of Fig. 1*l*.

2. Intensities of sound are usually expressed in decibels (db). For example, the difference in decibels of 100 musical instruments compared with 10 instruments, all of them supposed to be practically equal in intensity and frequency in their emitted sounds, is found to be:

$$\text{db} = 10 \log_{10} \frac{100}{10} = 10 \times 1 = 10\text{db}$$

Calculate the difference in decibels between the intensity of one sound and a second sound that has twice the intensity of the first. (*Ans*. 3 db.)

INTENSITY LEVEL

1. By inspection of Fig. 1*o*, find the decibel difference between the threshold of audibility and the threshold of feeling for a tone whose frequency is 64 cycles/sec; for 512 cycles/sec; 4,096 cycles/sec.

2. Referring to Fig. 1*p*, estimate the intensity increase of a 100-cycle tone for which the equally loud 1,000-cycle tone increases from 70 to 80 db (approximately 6 db); also, estimate the increase of a 10,000-cycle tone for same 70 to 80 db increase of the 1,000-cycle tone. (*Ans*. Approx. 9 db.)

3. At which frequency, 100 cycles or 1,000 cycles, would you estimate the ear to be better able to detect small changes in sound intensity? (See Fig. 1*p*.)

4. Suppose that a radio is adjusted to give an intensity level of 60 db for all frequencies and then the volume control cuts all the sounds down 20 db. By inspection of Fig. 1*p*, show that the low-frequency sounds become almost inaudible by this change, but that sounds from 700 to 10,000 are about equally reduced.

LOUDNESS OF SOUND

(These problems involve the use of logarithms.)

In the graph of Fig. 1*q*, the section from 40 db (phons) to 100 db (phons) is a straight line — a range of values that includes most of the sounds and noises that occur in buildings. The equation for this straight line section is given by Fletcher (*Jour. Acous. Soc. Amer.*, Vol. 9, p. 280, 1938) which for calculation purposes may be written:

$$\log_{10} N = 3 + \frac{L - 40}{30}$$

in which N is the loudness number and L is the decibel (phon) value of the 1,000-cycle reference tone.

Example 1. Compare the loudness values of two sounds for which the 1,000-cycle reference levels are 40 phons and 70 phons.

$$\text{For } L = 70 \text{ phons: } \log N_2 = 3 + \frac{70 - 40}{30} = 4; \; N_2 = 10{,}000$$

$$\text{For } L = 40 \text{ phons: } \log N_1 = 3 + \frac{40 - 40}{30} = 3; \; N_1 = 1{,}000$$

Ans. $N_2 = 10 \times N_1$.

Example 2. To what value of the 1,000-cycle reference level must a 40-phon sound be raised until the final sound appears to be twice as loud as the original 40-phon sound?

In Example 1, the loudness, N_1, of the 40-phon sound is 1,000 units; so that, in this example, N_2 is 2,000 units, twice as loud as N_1. Substituting in the equation:

$$\log 2{,}000 = 3 + \frac{L - 40}{30}$$

from which $L = 49$ phons. The 40-phon sound must be increased to 49 phons to appear to be twice as loud.

Problem 1. According to Fig. 1*q*, a sound *A* whose loudness level is 100 phons appears to be 100 times as loud as a sound *B* whose loudness is 40 phons. How much louder would a sound *A* appear to be if its loudness level were 30 phons greater than the sound *B* of 40 phons?

Problem 2. Consulting Fig. 1*p*, confirm the fact that the number of decibels that a 100-cycle tone must have to correspond to a loudness level of 40 phons at 1,000 cycles is 63 db.

Using the loudness equation, show that the 100-cycle tone must be raised to 78 db to appear 10 times as loud as the original value.

Problem 3. An old riddle asks: " What makes more noise than a pig under a gate? " The answer is " two pigs." Assuming that the average intensity of the squeal of two pigs is twice the squeal of one pig, show that the intensity of the two pigs is 3 db greater than the intensity of one pig.

Show by Fletcher's equation that the loudness N of two pigs is 1.26 times as great as the loudness of one pig, assuming that the average frequency of the squeals is 1,000 cycles/sec.

CHAPTER III

1. Referring to Fig. 3*b*, draw diagram showing sound reflected *three* times between two parallel walls in passing from speaker to auditor, indicating positions of source, auditor, and images.

2. Repeat answer to problem 1, except that one of the reflections shall take place at the end wall.

3. Confirm the following data for sound reflected as shown in Fig. 3*a*:

Distance (d)	Time $t = d/v$	Intensity	Total Intensity	Decibel Level
20 ft (direct sound)	0.0179	10,000	10,000	40.
25 ft (1st reflection)	0.0223	6,400	16,400	42.14
30 ft (2nd reflection)	0.0268	4,444	20,844	43.2

That is, if the distance from speaker to auditor is 20 ft, the time taken to traverse this distance is 20/1,120 = 0.0179 second, where 1,120 ft/sec is the velocity of sound. Assuming that the intensity of this sound is 10,000 threshold units, the decibel level is calculated to be: 10 × log 10,000 = 40 db. In the same way the time for the first reflected sound to reach the auditor is 25/1,120 = 0.0223 second. The intensity of this sound is found by the relation that the intensity of spherical waves falls off inversely with the square of the distance from the source, so that the intensity, I_1, of the first reflected sound to the direct sound intensity, I_0, is $I_1/I_0 = (20/25)^2$, or $I_1 = (20/25)^2 \times 10{,}000 = 6{,}400$ threshold units. The total intensity for the two sounds is 16,400 units, for which the decibel level is 10 × log 16,400, or 42.1 db.

Problem. Confirm the results for the second reflected sound. How many times louder is the 43.2-db sound than the 40-db sound, assuming the frequency to be 1,000 cycles/sec? See Fig. 1*q*.

4. Sound from a singer at one end of a room passes 45 ft directly to an auditor at the other end of the room. At the same time, part of the sound is reflected from the walls, one beam of sound going 55 ft from singer to auditor, and a second beam going 60 ft. Calculate the time for each of the three sounds to pass from singer to auditor, if the velocity of sound is 1,120 feet/sec. Calculate the intensity in "threshold" units of the two reflected sounds at the position of the auditor, assuming that the intensity decreases inversely as the square of the distance from the singer, and that the intensity of the direct sound at the auditor's position is 10,000 threshold units.

Calculate the intensity level in decibels of the direct sound; also, the total decibels of the three sounds. (*Ans.* 43.5 db.)

5. State what the terms stand for in the equation for normal frequencies f in a room:

$$f = \frac{c}{2}\left[\left(\frac{b}{l}\right)^2 + \left(\frac{q}{w}\right)^2 + \left(\frac{r}{h}\right)^2\right]^{1/2}$$

(*a*) Show that the fundamental and overtone natural frequencies in the direction of the length ($l = 12$ ft) are: $46\frac{2}{3}$, $93\frac{1}{3}$, 140, etc., cycles/sec. Velocity of sound is 1,120 ft/sec.

(*b*) Show that the smallest dimension of a room for which "diffuse" sound will prevail is 40 ft, i.e., for which a sound of 280 cycles/sec has a wavelength that is one-tenth the smallest dimension of the room.

6. Using the equation for the normal modes of vibration in a room, show that the frequency of the lowest-pitched sound set up between the floor and ceiling, taking the ceiling height to be 9 ft, is 62 cycles/sec.

7. Calculate the lowest frequency of the normal mode vibrations in a rectangular room, 40 ft by 60 ft by 30 ft high.

8. Show that the smallest dimension allowable for a room in which the lowest frequency is to be 100 cycles/sec is 5.6 ft.

CHAPTER IV

1. Confirm the result that the time of reverberation is 1.25 seconds in the room of 100,000-cubic-foot volume and 20,000-square-foot area when the average absorbing coefficient of the surfaces is 0.20.

2. Deduce the value of the time of reverberation for the room in problem 1 by the Eyring equation.

3. Show that the value of $\log_e (1-\alpha)$ is approximately the same as $-\alpha$ when $\alpha = 0.2$ or less.

4. Calculate the number of reflections of sound required in a room of 400,000-cubic-foot volume and 50,000-square-foot area of interior surfaces to reduce the intensity of sound to one-millionth of its initial value if the absorbing value of the surfaces is 0.05. (*Ans.* 280 reflections.)

5. If the average absorption coefficient, a, in a room is equal to unity, meaning that the room has 100 per cent absorption, why should the time of reverberation be zero?

Which equation, Sabine's or Eyring's, fulfills this condition?

CHAPTER V

1. An auditorium in rectangular shape, 110 by 75 by 30 ft high. It has the following features:

(*a*) Plaster walls and ceiling, coefficient = 0.033
(*b*) Wood floor, coefficient = 0.03
(*c*) 1,000 seats at 0.1 each

Calculate the number of absorbing units in this room, when empty. (993 sabins, approximately.)

Calculate by Sabine's formula the time of reverberation in the room for no audience, for 300 auditors, and for 1,000 auditors. (For 300 auditors, $t = 5.2$ seconds.) Take absorption value of one auditor to be 4.7 sabins, subtracting 0.1 for each seat occupied.

Calculate the number of absorbing units that should be added to the room to give a time of reverberation of 1.7 seconds when 300 auditors are present, and calculate the coefficient of the absorbent needed to give this added absorption if it covers $\frac{4}{5}$ of the area of the side and rear walls. (*Ans.* 0.72.)

2. A rectangular room is 100 by 40 by 30 ft high, with wood floor, hard plaster walls and ceiling, and 550 seats of absorption coefficient of 0.25 per seat.

(*a*) Calculate the time of reverberation for 60-db decay. (8.95 sec.)

(*b*) Consult Fig. 6*b* and select an optimal time of reverberation for average conditions including speaking and music. (1.3 sec.)

(*c*) Assuming that this optimal time applies to one-third audience, calculate the number of units of absorbing material that should be added to the room.

(*d*) Without making numerical calculations, indicate where you would apply this material, giving briefly the reason for each choice.

(*e*) Would you recommend upholstered seats? Why?

(*f*) How would you change the shape of the room to secure better acoustical conditions; give reasons briefly for each change?

3. Confirm the following for problem 2; the average coefficient of absorption for the conditions as in (*a*) is 0.0406, and the number of reflections of the sound in decaying 60 db is 339. Calculate the mean free path of sound in the room (29.25 ft), the distance traversed by the sound in decaying 60 db, and the time taken for this 60 db decay (8.85 sec). Velocity of sound = 1.120 ft/sec.

CHAPTER VI

1. Explain why too long a time of reverberation in a room is undesirable.

2. Assuming a spherical auditorium, prove according to Sabine's formula ($t = 0.05V/as$) that the following relations hold: (*a*) for a = constant, t varies as the cube root of V; (*b*) for t = constant, a varies as the cube root of V. (Hint: substitute in the formula the value of $V = 4\pi r^3/3$ as volume of sphere, and $S = 4\pi r^2$ as area of a sphere.)

3. Consider two spherical auditoriums with volumes V_1 and V_2, with interior surface areas S_1 and S_2 and average absorption coefficients a_1 and a_2. Take $V_2 = 8V_1$.

Compare the absorption per square foot in V_1 with that in V_2 according to the condition of problem 2 (*a*). (*Ans.* $a_1 = a_2$.)

According to the condition 2 (*b*). (*Ans.* $2a_1 = a_2$.)

Compare the total absorption in V_1 with that in V_2 according to the condition 2 (*a*). (*Ans.* $4a_1S_1 = a_2S_2$.)

According to 2 (*b*). (*Ans.* $8a_1s_1 = a_2S_2$.)

4. Do the times of reverberation for problems 1 and 2, Chapter V, for the occupied and unoccupied rooms accord with the shaded region of Fig. 6*b* for optimal times of reverberation? Comments?

CHAPTER VII

1. State the two conditions set forth by Watson for ideal acoustics in an auditorium. What considerations led to this ideal?

2. (*a*) Draw a stage for the auditorium of problem 1, Chapter V, that will allow the performers to hear themselves.

What arrangements would you make to reduce normal mode resonances on the stage?

Describe the advantages of the stage.

(*b*) How would you arrange the absorption in this auditorium to approximate outdoor conditions, using upholstered seats and absorbing materials of various kinds and placement, and having the time of reverberation of 1.7 seconds, or less?

(*c*) How would you arrange the rear walls to minimize reflected sound?

(*d*) Would it be possible to get an optimal time of 1.7 seconds on the stage, assuming usual absorption values for the interior surfaces, and estimating the absorption of the stage opening toward the audience to have a coefficient of 0.75?

CHAPTER VIII

1. What three factors should be considered in the acoustic design of auditoriums? Draw rough sketches of the plan and sections of an auditorium that will have the three desirable factors for ideal acoustics.

2. Draw sketch of a church pulpit with a sounding board; also with the microphone and loud-speaker of a sound-amplifying system.

3. Which would be more advantageous for good acoustics, to have a ventilating system with the warm air entering at the ceiling and leaving at the floor, or vice versa? Can you think of a better arrangement than either of these systems?

4. Design a band practice room for, say, 75 players, approximating as closely as possible the conditions for ideal acoustics.

5. Referring to Fig. 8*f*, confirm the following results. Assuming that the intensity of the sound reaching the auditor from the flat ceiling is 2,450 threshold units.

show that it is 34 db above the threshold intensity of 1 unit. Assuming that the sound reflected to the auditor is 1,000 times greater from the dome ceiling than from the flat ceiling, show that the sound from the curved ceiling has 2,450,000 units of threshold intensity and is 64 db above the unit threshold intensity.

CHAPTER IX

1. Consider a cruciform church auditorium, that is, one in which the floor plan is in the shape of a cross. Assume that the auditorium has a high ceiling of Gothic design (inverted V shape), that the sanctuary has a back wall that is cylindrical in shape and with a ceiling in the shape of a quarter-sphere dome. What arrangements could you suggest for this auditorium that will aid in getting good acoustics?

2. Many theaters have a back wall curved to conform to the rear row of seats. Name three methods by which the concentration of sound by this wall could be minimized.

3. Consider the acoustical treatment of the dome in Figs. 9*h* and 9*i*. Remembering that sound is reflected, absorbed, and diffracted, explain how this construction would break up regular reflection and concentration of sound.

4. Discuss the acoustic features of a broadcasting room, indicating absorption arrangements that will make the room extremely dead for sounds of various frequencies and also suggesting means by which performers can hear themselves.

CHAPTER X

Refer to Knudsen's equation: $P = 96\, k_l k_r k_n k_s$.

1. (*a*) Calculate the percentage articulation for an auditorium in which $k_s = 1$, the loudness level is 40 db, the reverberation is 3 seconds, and the ratio of noise level to speech is 0.5. (*Ans.* $P = 57$ per cent.)

(*b*) What changes could you make to raise this percentage to $P = 80$ per cent?

2. In an auditorium, with $k_s = 1$, with loudness level = 70 db, and the ratio of noise level to speech = 0.3, the percentage articulation was measured to be 52 per cent. What was the reverberation time?

3. Referring to Fig. 10*d*, and Knudsen's statement that the articulation decreases about 6 per cent for each second increase in the time of reverberation, show that the value of k_r may be given approximately by the relation:

$$K_r = 1 - 0.06\ (t - 0.5)$$

where t is the time of reverberation. Verify by letting $t = 2$ seconds. Would the equation give the same value as the curve in Fig. 10*d* for $t = 6$?

4. Assuming the value of k_s as unity, find two sets of values for loudness, reverberation, and noise ratio that will give $P = 85$ per cent.

CHAPTER XI

1. In an articulation test, the number of words heard incorrectly was 2 out of 25, and 8 consonants were missed out of 50. Calculate the percentage articulation.

2. Assuming in problem 1 that the test was made in a room with the time of reverberation of 5.2 seconds. By inspection of Fig. 10*d*, show that reducing the time of reverberation to 3.4 seconds would give 80 per cent articulation.

3. When a sound-amplifying system has two loud-speakers, why should they be placed close together? Why is it desirable to have one-loud speaker for low-frequency sounds and one for high frequencies?

4. Draw diagram showing arrangement of *two* loud-speakers to give approximate uniform distribution of sound in an auditorium. See Fig. 3*i*.

5. Why would a loud-speaker at the back of a room give sounds comparable with an echo?

An auditor is midway between a loud-speaker and a wall 100 ft away. Calculate the time interval between the sound reaching the auditor directly from the loud-speaker and the sound reaching him after reflection from the wall. Will this reflected sound be perceived as an echo? Look up "Echo" in Chapter I. Velocity of sound is 1,120 ft/sec.

CHAPTER XII

1. What becomes of sound in a room? Explain how sound is absorbed at a plaster wall; by a porous material.

2. Explain the statement: the coefficient of sound absorption of a material is 0.55.

3. Using the reverberation equation, it may be shown that:

$$a_0 s_0 t_0 = (a_0 s_0 + a_1 s_1) t_1$$

where $a_0 s_0$ is the absorption of the bare room, $a_1 s_1$ is the absorption of the material added to the room, and t_0 and t_1 are the times of reverberation when the room is bare and when the material is added respectively. This equation assumes that the energy of sound in the room remains constant.

(*a*) According to the equation, calculate the approximate absorption coefficient of hairfelt from the following data: time of reverberation of the bare room = 4.96 seconds; time with 72 sq ft of hairfelt on floor = 3.53 seconds; value of $a_0 s_0$ for bare room, frequency 512 = 90.2 sabins. (*Ans.* 0.5.)

4. An experimental sound room has a volume of 1,000 cu ft and a reverberation time of 10 seconds. If 40 sq ft of an absorbing material is brought into the room and reduces the time of reverberation to 2 seconds, calculate by the Sabine equation the coefficient of absorption of the material.

CHAPTER XIII

1. Solve again problem 2, Chapter V, with the added condition of a wooden balcony built across the rear of the room, 20 ft wide, with steps that make the back of the balcony 8 ft higher than the front. Assume that the balcony adds 200 seats each with 0.1 sabin absorption. Would the changed values be greater or less than the 5 per cent variation allowed: (*a*) for the volume, (*b*) for the absorption of the empty room, (*c*) for the time of reverberation for the empty room?

2. P. E. Sabine states that the absorption in an empty room with hard plaster walls and ceiling cement (or wood) floor, and plain seats can be obtained approximately by the equation:

$$aS = 0.29 \times (\text{volume})^{2/3}$$

Calculate the absorption by this equation for problem 2, Chapter V, and compare it with the solution already made. Does the difference in results come within the 5 per cent variation allowed?

CHAPTER XIV

1. What acoustical treatment would you prescribe (*a*) for an office space 50 by 50 by 10 ft high; (*b*) for a small office in which great quiet is desired?

2. Consult Fig. 14*d*. Suppose that a person is telephoning so that the intensity level of his voice 1 ft away is 70 db. What would be the intensity level of his voice for a listener 30 ft from the telephone: (*a*) outdoors; (*b*) in a room with a low ceiling acoustically treated; (*c*) in the room without acoustical treatment? (*Ans.* (*b*) 46 db.)

According to Fig. 1*q*, how loud would the sound appear to the listener compared with the 70-db sound if he were in the position (*a*)? (*b*)? (*c*)? Assume that the intensity levels apply to 1,000 cycles.

3. What is the longest distance that a listener can hear the telephone conversation of problem 2, for cases (*b*) and (*c*), assuming that the sounds he can understand must be 15 db above the general room noise level of 40 db?

4. According to Fig. 14*a*, calculate the decibel reduction in sound level if the absorption in a room is increased fivefold. According to Fig. 1*q*, how loud would the reduced noise appear compared with the noise in the room without the added treatment? Assume that the average frequency of the sound is 1,000 cycles/sec, and that the loudness level originally was 70 phons.

5. Calculate the reverberation time for the empty room, as illustrated in Table 5*a*, Chapter V, for the frequency of 128; also for the frequency 2,048, using the coefficients of Table 12*b*. How would you correct the room for the frequencies 128 and 2,048, following the suggestions of Potwin in Fig. 6*i*, for the acceptable times of reverberation at these frequencies.

CHAPTER XV

1. Describe the three processes by which sound is transmitted from one room through a partition to another room. Rate the processes in order of importance.

2. Lamb (*Dynamical Theory of Sound,* Sec. 9) shows that the displacement of q of a partition depends on the inertia (mass) a and the elasticity (stiffness) c, by the formula

$$q = \frac{Q}{a(n^2 - p^2)}$$

where Q is the vibrating force of frequency P ($p = 2\pi P$) and $n^2 = c/a = (2\pi N)^2$, where N is the natural frequency of the partition.

Compare the displacements, q, for:

(*a*) $N = 20$ vib/sec and $P = 100$ vib/sec.
(*b*) $N = 200$ vib/sec and $P = 10$ vib/sec.

3. A sound of 70-db intensity level in one room is reduced to 65 db by absorption at the walls, then to 35 db on transmission through a partition, and finally to 30 db by absorption in the last room. Assuming that 0 db corresponds to 1 "threshold" unit of intensity, calculate the intensities of the sound for 70-, 65-, 35-, and 30-db levels. (*Ans.* for 70 db; 10,000,000 threshold units.)

According to Fig. 1*q*, assuming that the sound has a frequency of 1,000 cycles/sec calculate the loudness reduction from the 70-db level to the 35-db level, assuming Fletcher's equation to hold over that range.

What would the loudness reduction be if the frequency of the sound were 100 cycles/sec? Consult Fig. 1*p*.

4. Consulting Table 15*c*, which material would give the closest approximation to a 40-db reduction required of a partition?

CHAPTER XVI

1. Under what conditions will a cork pad under a vibrating machine reduce the amplitude of vibrations reaching the floor?

Under what circumstances will it increase the amplitude?

Under what circumstances is it desirable to use a damping material to insulate vibrations? When is damping detrimental? See Fig. 16*c*.

2. It is shown in books on mechanics that the natural, or resonant, frequency, f, of vibration of an elastic system of a mass resting on springs is given by the equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{s}}$$

where g is the acceleration of gravity equal to 32.2 ft/sec^2, and s is the distance in feet the mass sinks when placed on the springs.

Problem. The statement is made that car springs will deflect as much as 10 in. under static load. Show that the resonant frequency for this deflection is approximately 1 cycle/sec.

3. An electric motor with 1,800 rpm is mounted on a platform which is insulated from the floor by springs.

Calculate the frequency of vibration of the system of platform (including the motor) and springs, if the weight of the platform and motor, motor not running, depresses the springs 0.25 in.

According to Hull's equation, calculate the amount of vertical vibration is reduced under these circumstances. (*Ans.* 1/21.8.)

CHAPTER XVII

1. Design a quiet hotel bedroom. The room should be as nearly soundproof as possible, so that talking in it will not be transmitted outside; also, the outside sounds of bathrooms, talking, etc., will not disturb the occupant of the room. What arrangements can be made for heating and ventilation that will be quiet? Doors and windows? Partitions? Draw diagram showing the room; also the adjacent rooms and hallway.

2. What effect on the intensity of sound in a pipe is given by friction? By yielding of the sides of the pipe? By leaky joints?

3. Assume that the attentuation in decibels of the intensity of sound in a pipe varies directly as the length of the pipe and directly as the absorption coefficient of the inside lining but inversely as the diameter of the pipe. Suppose that a sound of 1,000,000-threshold-unit intensity is attenuated 10 db in traveling 10 ft in a pipe of 6-in. diameter with an inside lining of absorbing coefficient a.

(*a*) What coefficient of absorption of inside lining will be needed to give 5-db reduction in the sound in traveling 10 ft?

(*b*) What length of a second pipe of twice the diameter of the first would be needed to give a 2-db reduction in the sound in traveling 10 ft?

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